US009462668B2

(12) **United States Patent**
Tao et al.

(10) **Patent No.: US 9,462,668 B2**
(45) **Date of Patent: Oct. 4, 2016**

(54) **TARGET FOR EXTREME ULTRAVIOLET LIGHT SOURCE**

(71) Applicant: **ASML Netherlands B.V.**, Veldhoven (NL)

(72) Inventors: **Yezheng Tao**, San Diego, CA (US); **Robert Jay Rafac**, Encinitas, CA (US); **Igor Vladimirovich Fomenkov**, San Diego, CA (US); **Daniel John William Brown**, San Diego, CA (US); **Daniel James Golich**, San Diego, CA (US)

(73) Assignee: **ASML Netherlands B.V.**, Veldhoven (NL)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/874,164**

(22) Filed: **Oct. 2, 2015**

(65) **Prior Publication Data**

US 2016/0029471 A1 Jan. 28, 2016

Related U.S. Application Data

(63) Continuation of application No. 14/550,421, filed on Nov. 21, 2014, now Pat. No. 9,155,179, which is a continuation of application No. 14/310,972, filed on Jun. 20, 2014, now Pat. No. 8,912,514, which is a continuation of application No. 13/830,380, filed on Mar. 14, 2013, now Pat. No. 8,791,440.

(51) **Int. Cl.**

H05G 2/00 (2006.01)
H01S 3/10 (2006.01)
G21K 5/02 (2006.01)

(52) **U.S. Cl.**

CPC ***H05G 2/008*** (2013.01); ***G21K 5/02*** (2013.01); ***H01S 3/10*** (2013.01); ***H05G 2/005*** (2013.01)

(58) **Field of Classification Search**

CPC H05G 2/008; H05G 2/003; H05G 2/005; H05G 2/006; G03F 7/70033; G03F 7/70175; G03F 7/70916

USPC .... 250/504 R, 493.1, 423 R, 424, 489, 250/492.1, 492.2, 494.1, 503.1; 355/67

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,973,164 B2 12/2005 Hartlove
7,239,686 B2 7/2007 Berglund

(Continued)

FOREIGN PATENT DOCUMENTS

WO 2011/102277 A1 8/2011
WO 2011/122397 A1 10/2011

OTHER PUBLICATIONS

Larsen. Jon T., "Absorption and Profile Modification on Spherical Targets for .25 < λ < 2 microns," Presentation at the 8th Annual Conference on Anomalous Absorption of Electromagnetic Waves, Apr. 19-21, 1978, 48 pages.

(Continued)

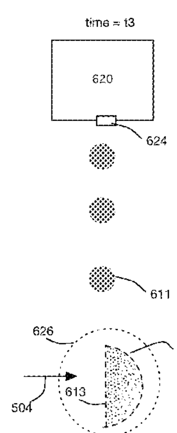
Primary Examiner — David A Vanore

(74) *Attorney, Agent, or Firm* — DiBerardino McGovern IP Group LLC

(57) **ABSTRACT**

Techniques for forming a target and for producing extreme ultraviolet light include releasing an initial target material toward a target location, the target material including a material that emits extreme ultraviolet (EUV) light when converted to plasma; directing a first amplified light beam toward the initial target material, the first amplified light beam having an energy sufficient to form a collection of pieces of target material from the initial target material, each of the pieces being smaller than the initial target material and being spatially distributed throughout a hemisphere shaped volume; and directing a second amplified light beam toward the collection of pieces to convert the pieces of target material to plasma that emits EUV light.

26 Claims, 15 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

7,491,954	B2	2/2009	Bykanov	
7,608,846	B2 *	10/2009	Nakano	H05G 2/005 250/493.1
7,916,388	B2	3/2011	Bykanov	
7,923,705	B2	4/2011	Moriya	
7,999,241	B2 *	8/2011	Nagai	G03F 7/70033 250/423 R
8,242,472	B2 *	8/2012	Moriya	H01S 1/1305 250/492.1
8,324,600	B2 *	12/2012	Hayashi	H05G 2/006 250/493.1
8,436,328	B2	5/2013	Yanagida	
9,113,540	B2 *	8/2015	Hori	H01S 3/10061
9,167,678	B2 *	10/2015	Hori	H01S 3/10061
9,232,624	B2 *	1/2016	Rafac	G21K 5/00
9,265,136	B2 *	2/2016	Hori	H01S 3/2232
2006/0255298	A1	11/2006	Bykanov	
2010/0051831	A1	3/2010	Tao	
2010/0078577	A1 *	4/2010	Moriya	H05G 2/005 250/504 R
2010/0181503	A1	7/2010	Yanagida	
2011/0057126	A1 *	3/2011	Hoshino	H01S 3/2383 250/504 R
2011/0317256	A1	12/2011	Hou	
2012/0092746	A1	4/2012	Hou	
2012/0228525	A1 *	9/2012	Moriya	H05G 2/003 250/504 R
2012/0235066	A1	9/2012	Ershov	
2012/0243566	A1	9/2012	Hori	
2012/0248344	A1 *	10/2012	Wakabayashi	H05G 2/008 250/504 R
2012/0305811	A1 *	12/2012	Wakabayashi	H05G 2/008 250/504 R
2012/0307851	A1	12/2012	Hori	
2012/0313016	A1 *	12/2012	Fleurov	H05G 2/008 250/504 R
2012/0319014	A1 *	12/2012	Moriya	H01S 3/1305 250/504 R
2013/0146682	A1 *	6/2013	Ishihara	G03F 7/70033 239/590
2014/0183379	A1 *	7/2014	Hori	H01S 3/10061 250/504 R

OTHER PUBLICATIONS

Garban-Labaune et al., "Resonance Absorption in CO2 Laser-Plane Targets Interaction Experiments", Journal De Physique-Lettres, vol. 41, No. 19, Oct. 1980, pp. 463-467.

Nakano et al., "Sn Droplet Target Development for Laser Produced Plasma EUV Light Source," Proc. SPIE, Emerging Lithographic Technologies XII, vol. 6921, 2008, 8 pages.

Fujimoto et al.,"Development of Laser-Produced Tin Plasma-Based EUV Light Source Technology for HVM EUV Lithography", Physics Research International, vol. 2012, Article ID 249495, Jun. 2012, pp. 1-11.

International Search Report and Written Opinion received for PCT Patent Application No. PCT/US2014/017496, mailed Mar. 20, 2014, 7 pages.

* cited by examiner

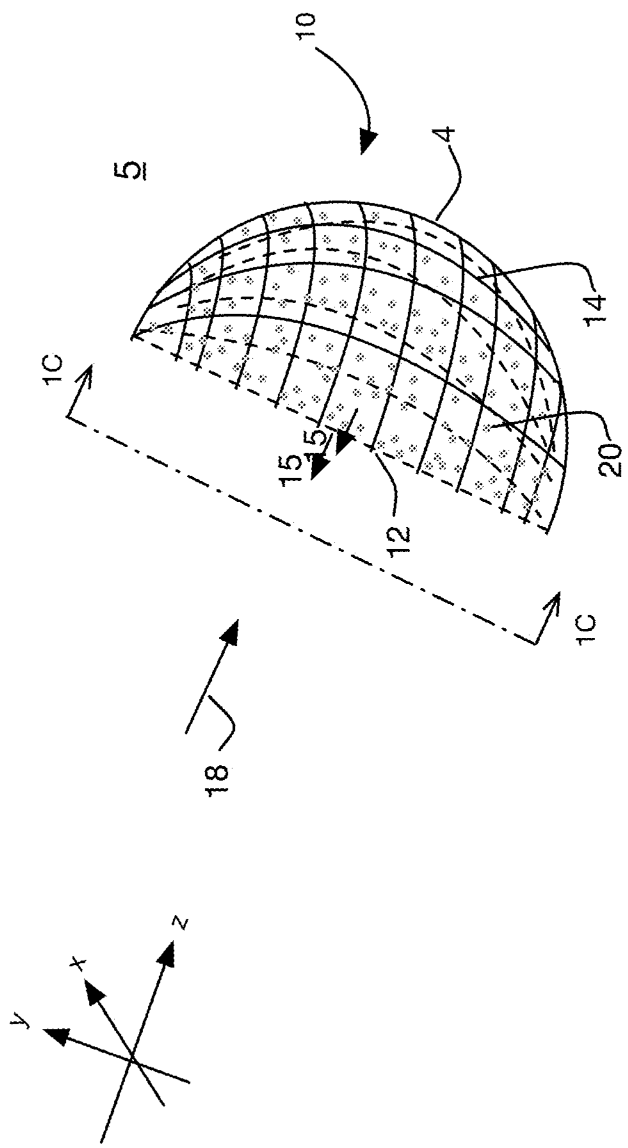


FIG. 1A

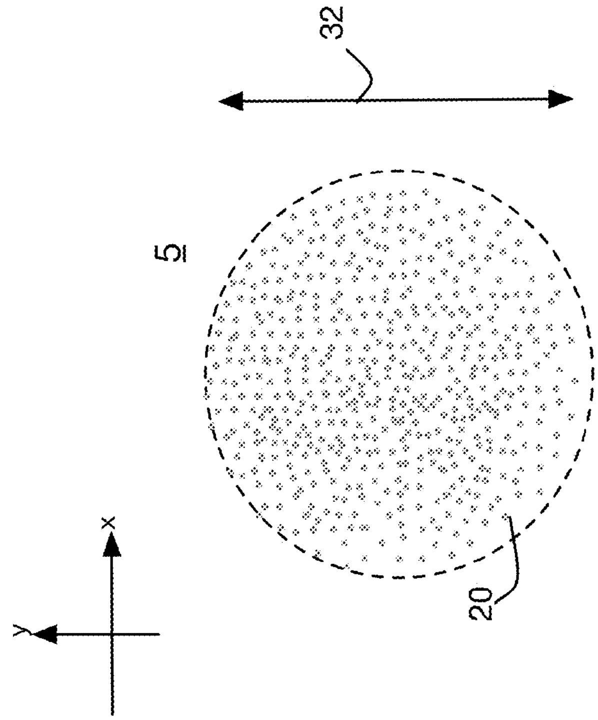


FIG. 1C

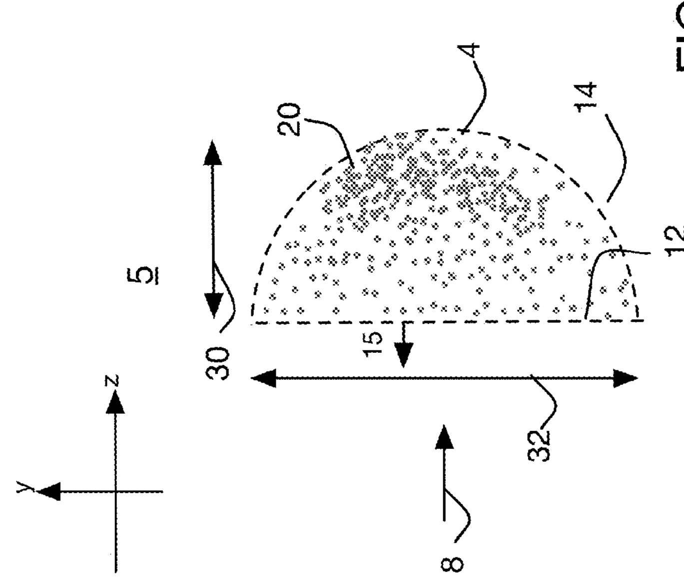


FIG. 1B

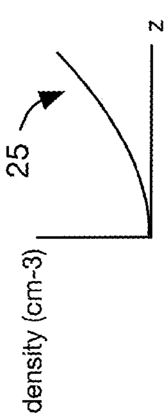


FIG. 1D

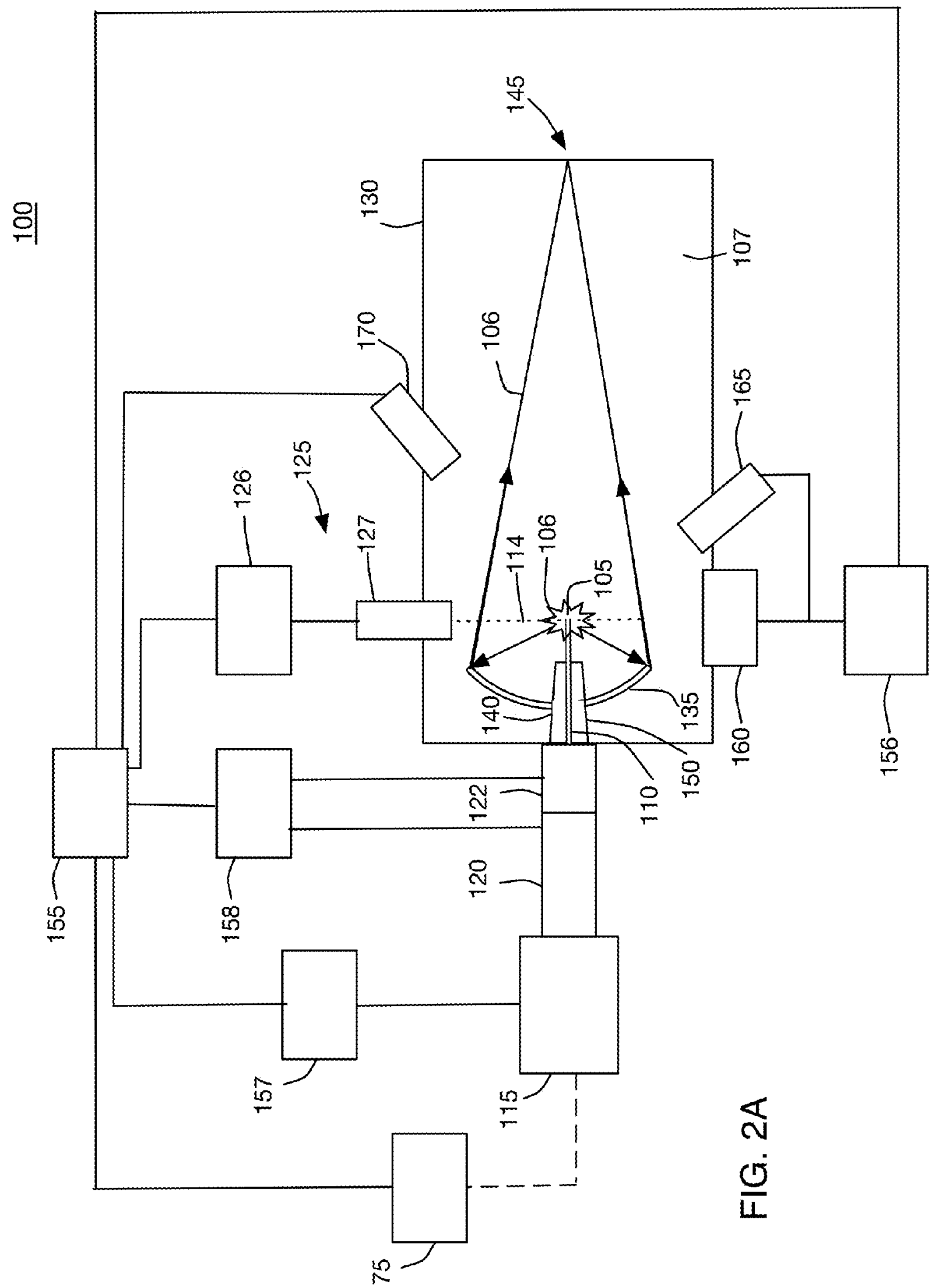

100
145
130
107
106
170
165
126
125
127
114
106
105
140
135
150
110
160
156
122
120
155
158
157
115
175

FIG. 2A

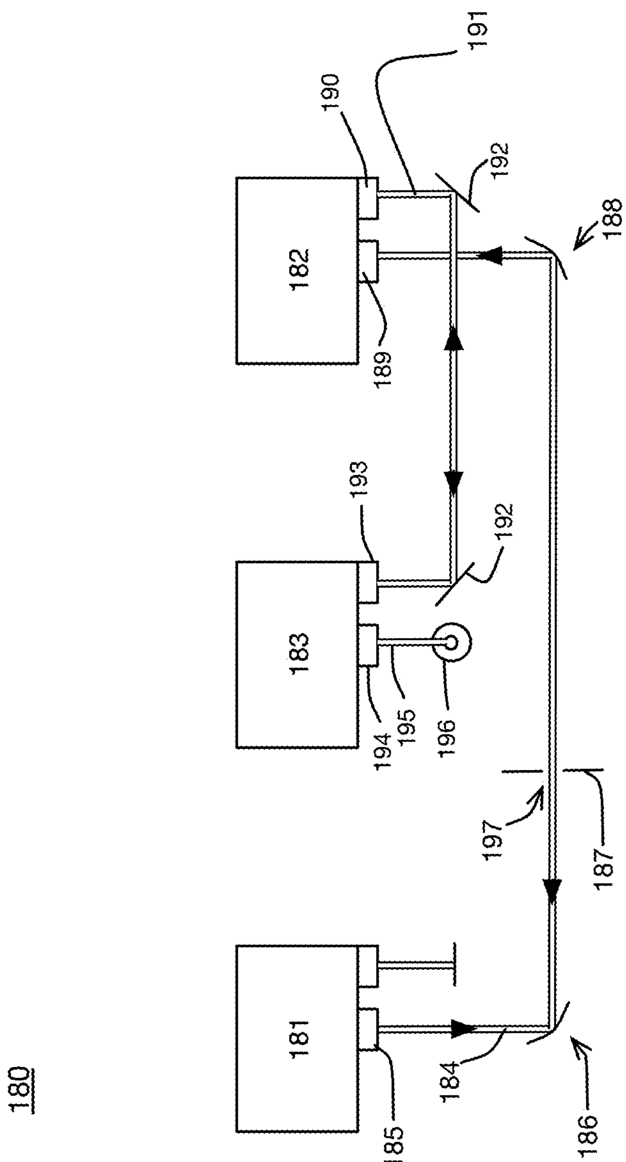

180
181
182
183
184
185
186
187
188
189
190
191
192
192
193
194
195
196
197

FIG. 2B

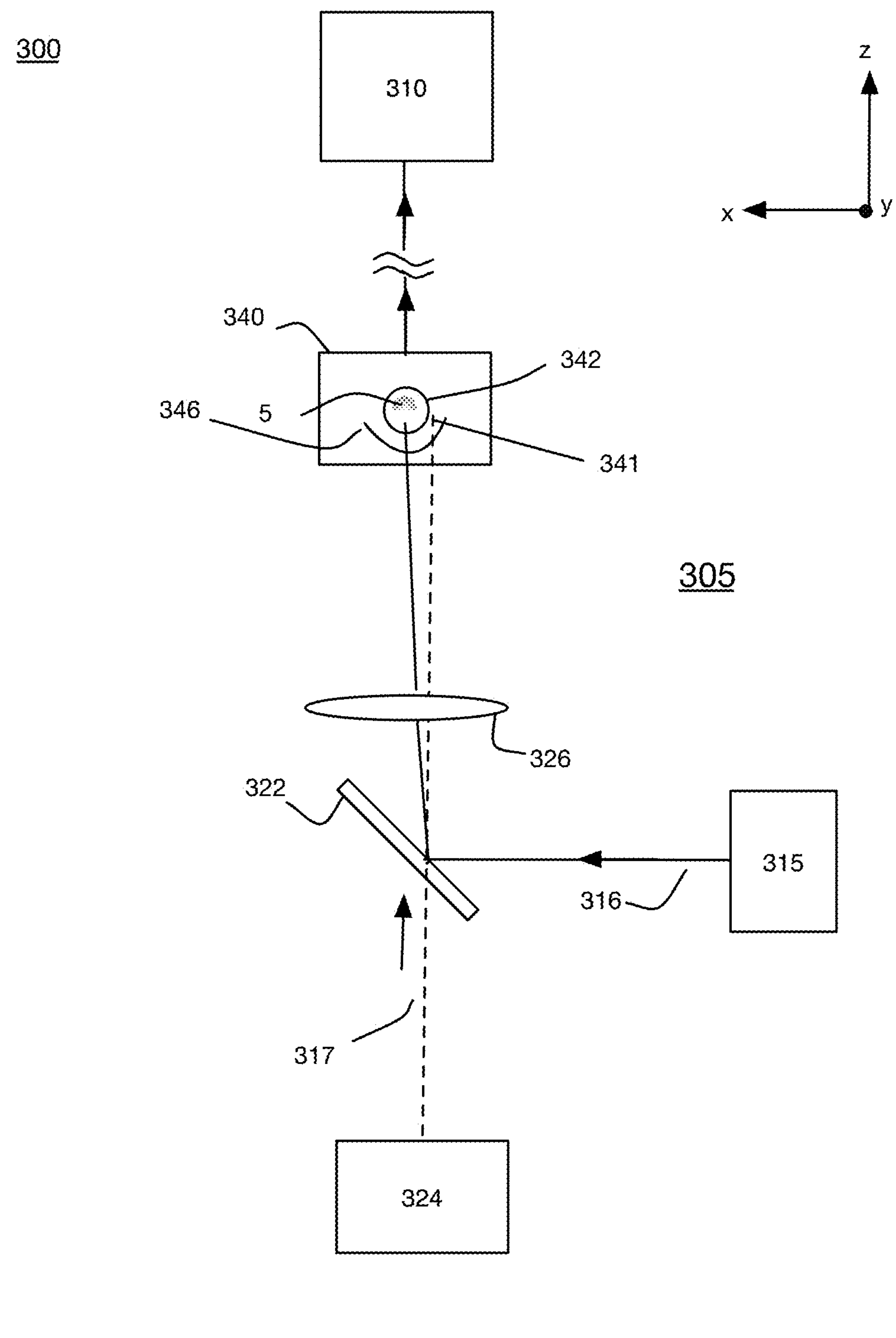
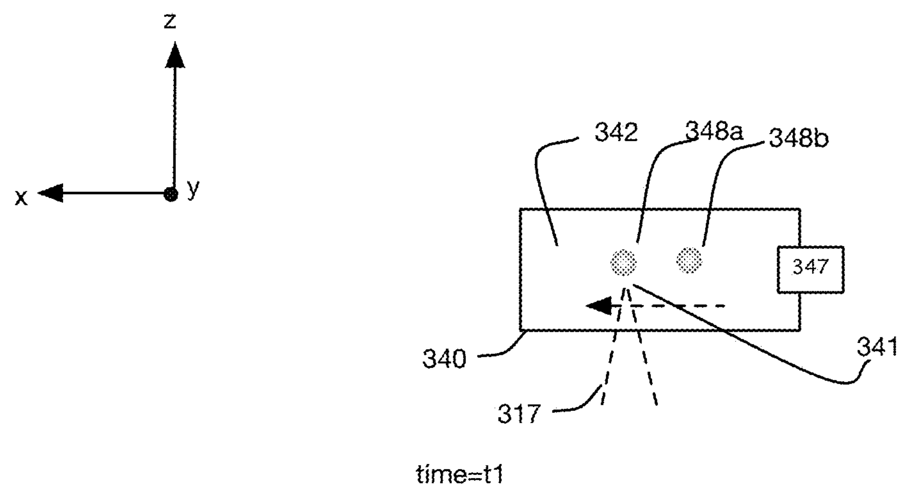
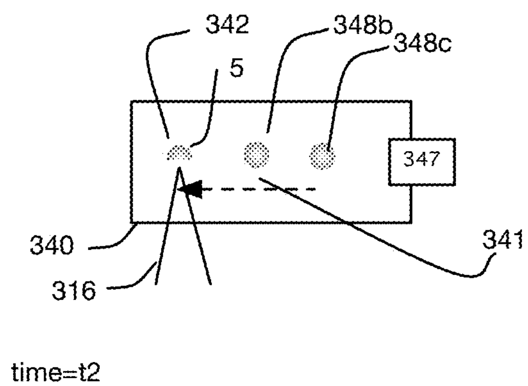


FIG. 3A



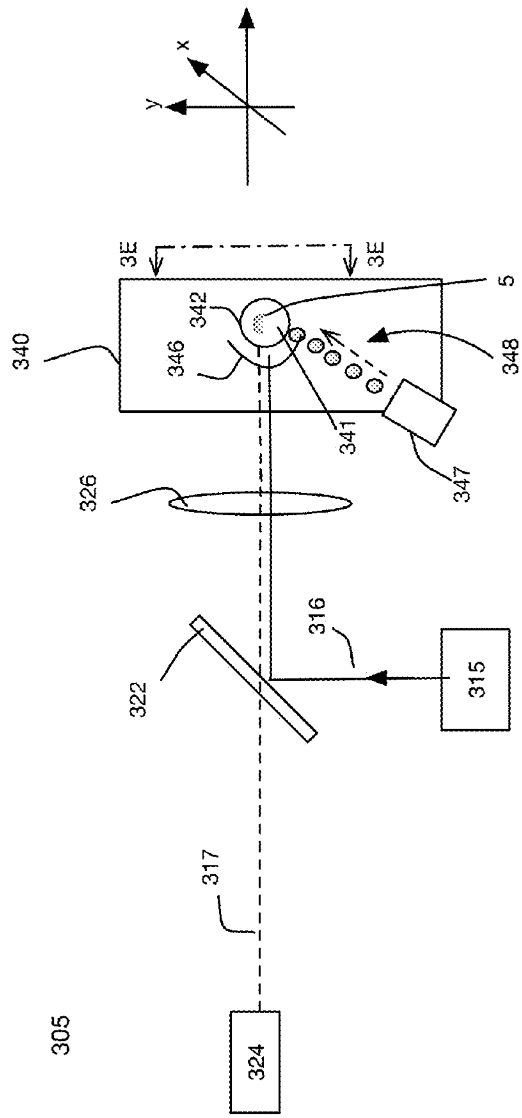
z
x
y
342
348a
348b
347
340
341
317
time=t1

FIG. 3B



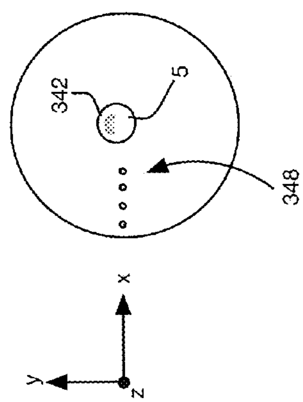
342
348b
348c
5
347
340
341
316
time=t2

FIG. 3C



x
y
3E
3E
340
342
5
346
348
341
347
326
316
322
315
317
305
324

FIG. 3D



342
5
348
x
y
z

FIG. 3E

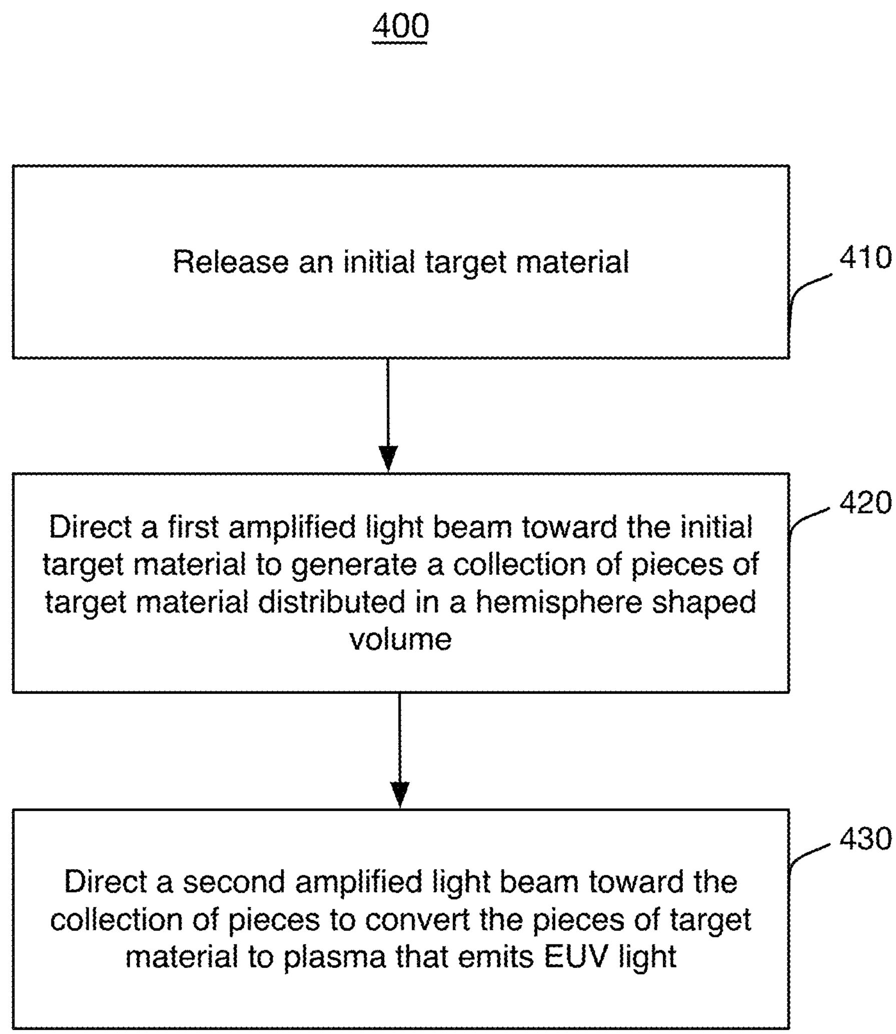

400
Release an initial target material
410
Direct a first amplified light beam toward the initial target material to generate a collection of pieces of target material distributed in a hemisphere shaped volume
420
Direct a second amplified light beam toward the collection of pieces to convert the pieces of target material to plasma that emits EUV light
430

FIG. 4

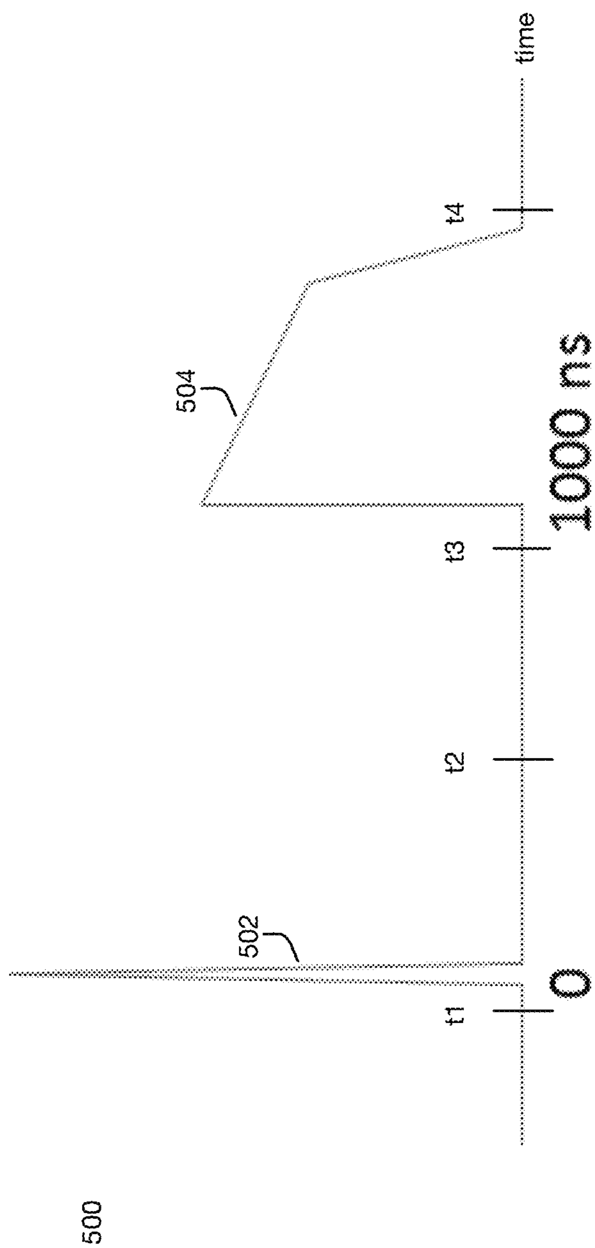


FIG. 5

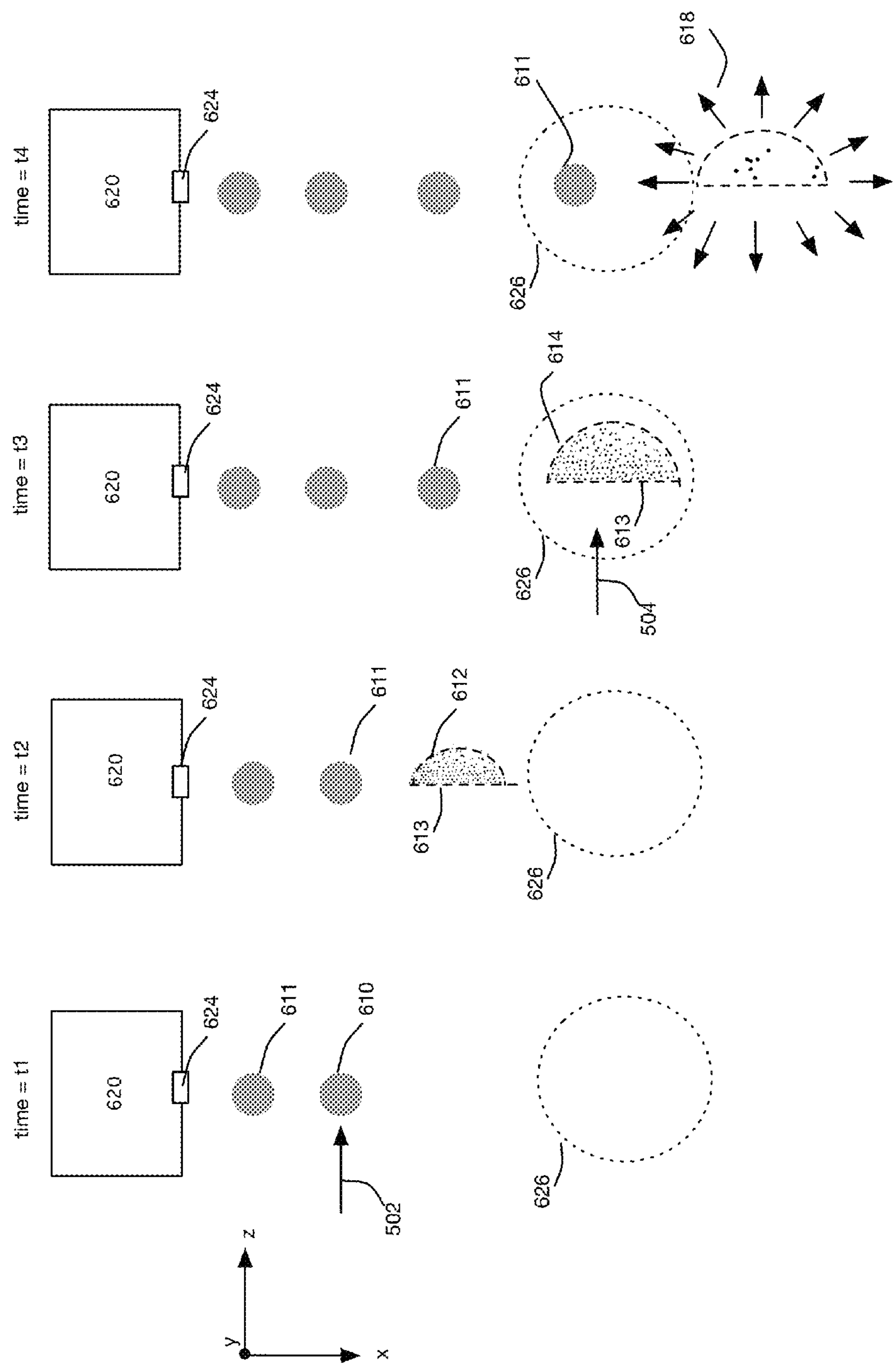
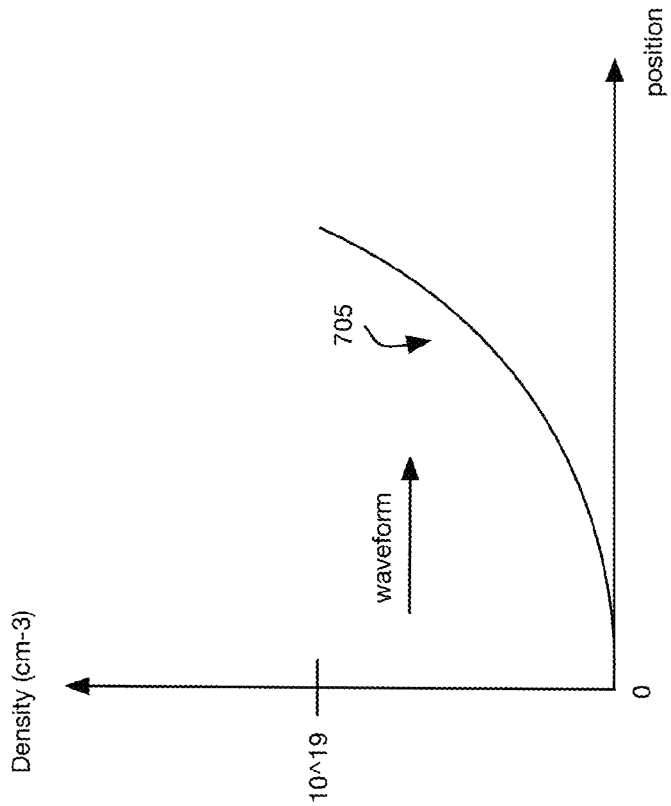


FIG. 6A

FIG. 6B

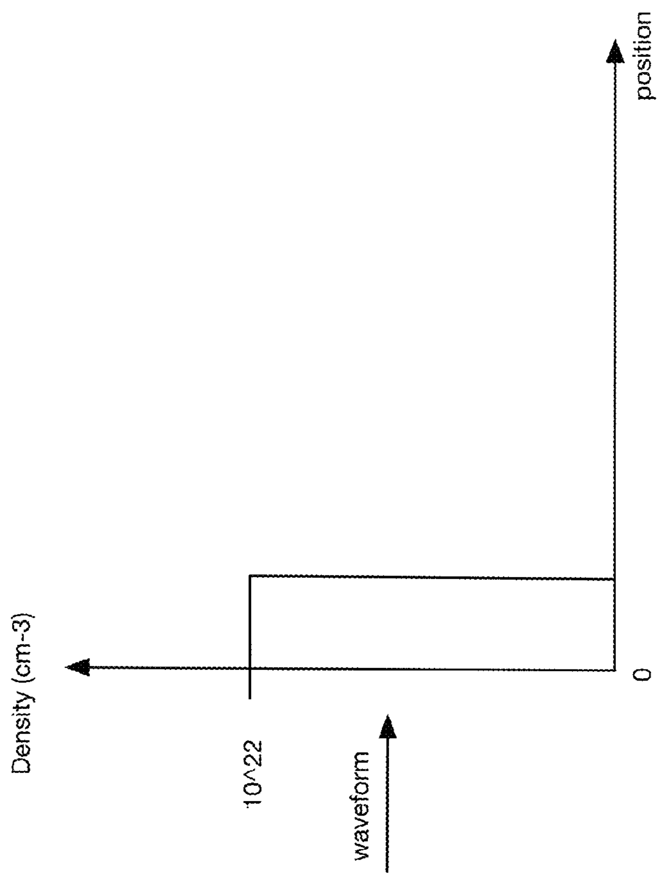
FIG. 6C

FIG. 6D



Density (cm-3)
10^19
0
waveform
705
position

FIG. 7B



Density (cm-3)
10^22
waveform
0
position

FIG. 7A

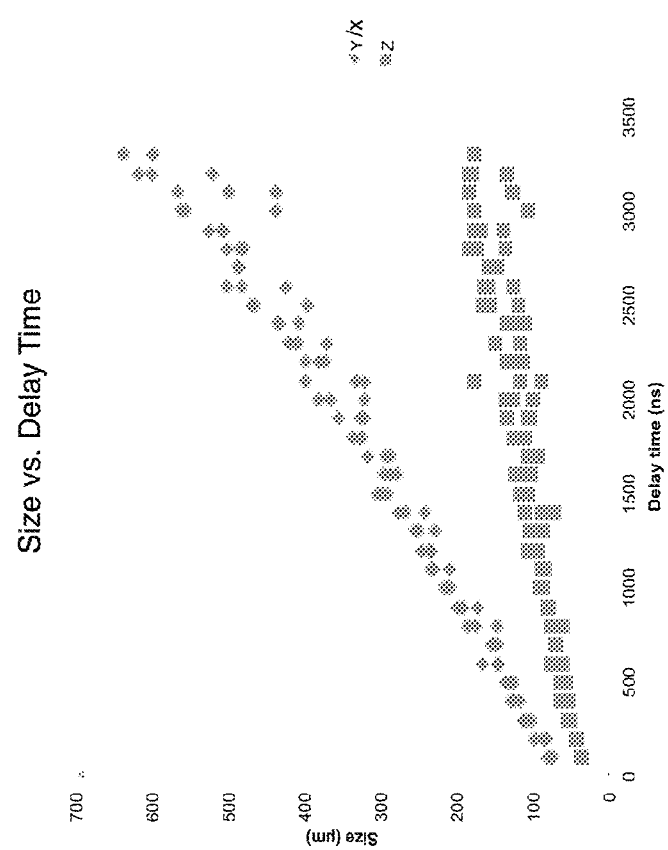

Size vs. Delay Time
Size (μm)
700
600
500
400
300
200
100
0
Delay time (ns)
0
500
1000
1500
2000
2500
3000
3500
Y/x
Z

FIG. 8A

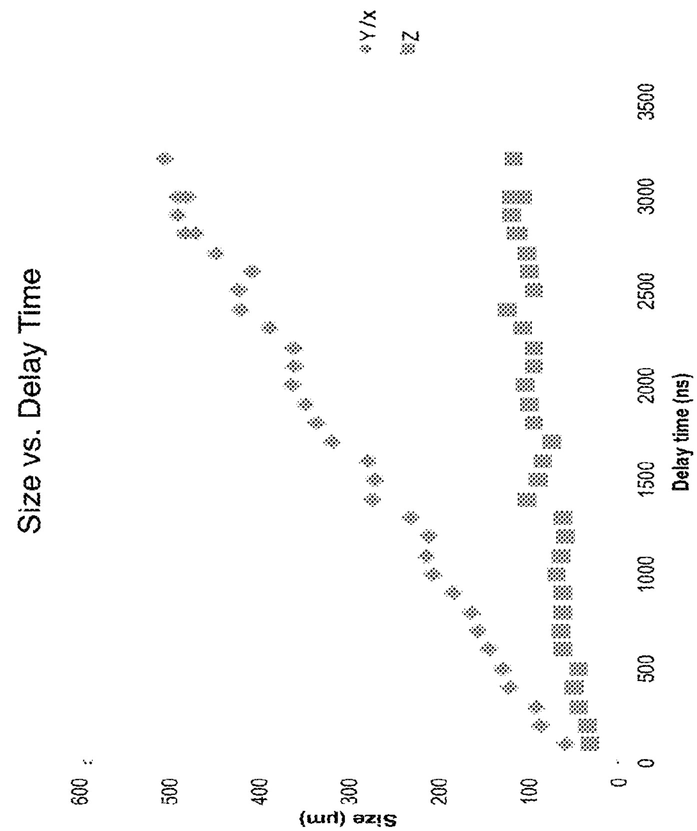

Size vs. Delay Time
Size (μm)
600
500
400
300
200
100
0
Delay time (ns)
0
500
1000
1500
2000
2500
3000
3500
Y/x
Z

FIG. 8B

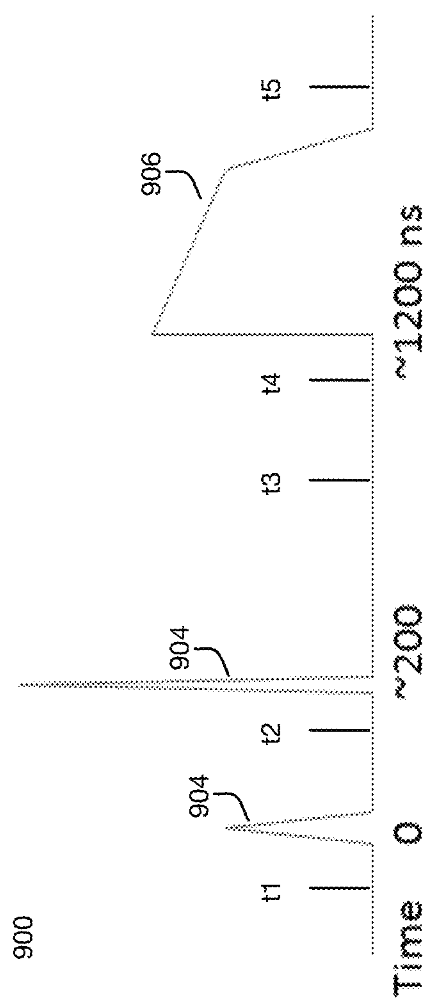


FIG. 9

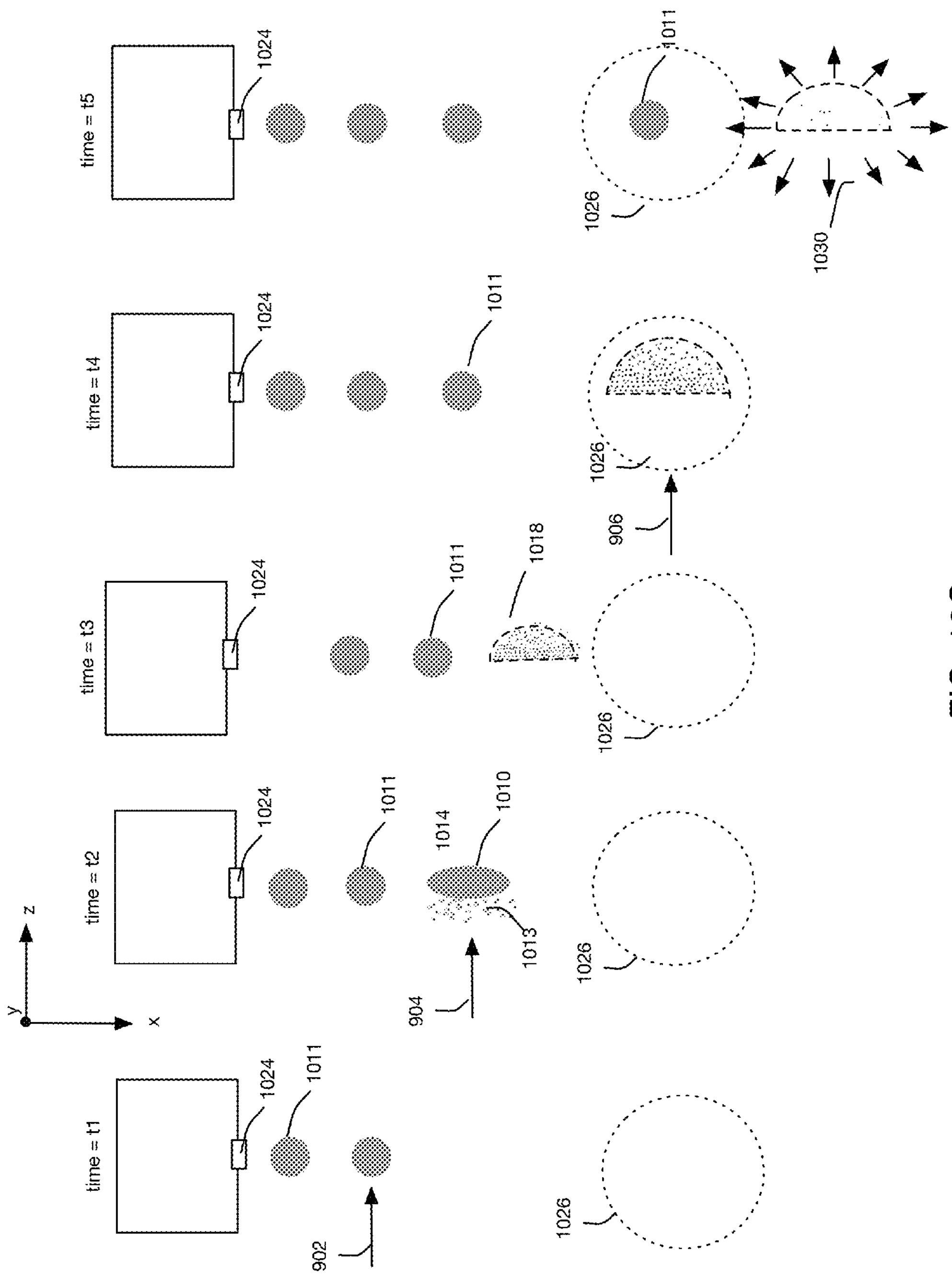


FIG. 10A

FIG. 10B

FIG. 10C

FIG. 10D

FIG. 10E

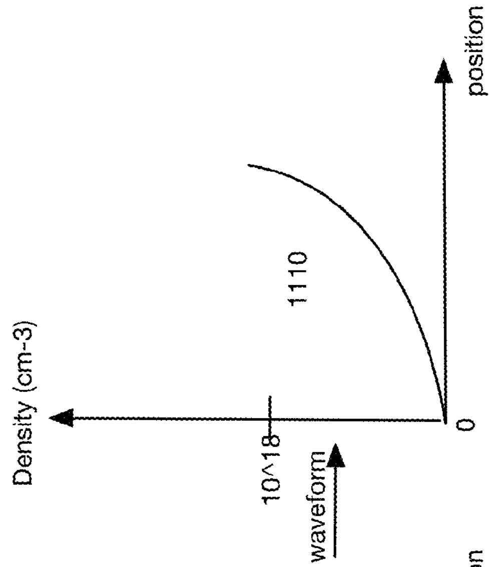


FIG. 11C

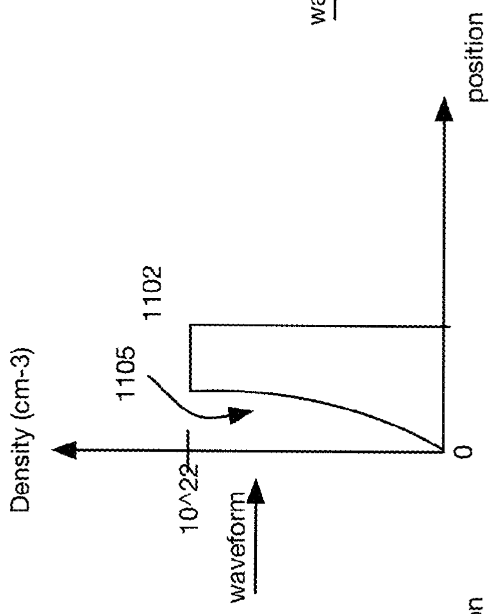


FIG. 11B

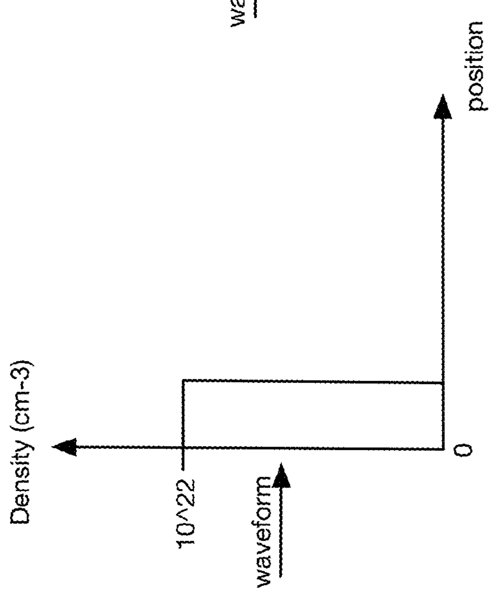


FIG. 11A

TARGET FOR EXTREME ULTRAVIOLET LIGHT SOURCE

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation of U.S. patent application Ser. No. 14/550,421, filed Nov. 21, 2014, which continuation of U.S. patent application Ser. No. 14/310,972, filed Jun. 20, 2014, now granted as U.S. Pat. No. 8,912,514, issued on Dec. 16, 2014, which is a continuation of U.S. patent application Ser. No. 13/830,380, filed Mar. 14, 2013, now granted as U.S. Pat. No. 8,791,440, issued on Jul. 29, 2014, each of which is titled TARGET FOR EXTREME ULTRAVIOLET LIGHT SOURCE, and each of which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

The disclosed subject matter relates to a target for an extreme ultraviolet (EUV) light source.

BACKGROUND

Extreme ultraviolet (EUV) light, for example, electromagnetic radiation having wavelengths of around 50 nm or less (also sometimes referred to as soft x-rays), and including light at a wavelength of about 13 nm, can be used in photolithography processes to produce extremely small features in substrates, for example, silicon wafers.

Methods to produce EUV light include, but are not necessarily limited to, converting a material that has an element, for example, xenon, lithium, or tin, with an emission line in the EUV range into a plasma state. In one such method, often termed laser produced plasma (LPP), the plasma can be produced by irradiating a target material, for example, in the form of a droplet, plate, tape, stream, or cluster of material, with an amplified light beam that can be referred to as a drive laser. For this process, the plasma is typically produced in a sealed vessel, for example, a vacuum chamber, and monitored using various types of metrology equipment.

SUMMARY

In one general aspect, a method includes releasing an initial target material toward a target location, the target material including a material that emits extreme ultraviolet (EUV) light when converted to plasma; directing a first amplified light beam toward the initial target material, the first amplified light beam having an energy sufficient to form a collection of pieces of target material from the initial target material, each of the pieces being smaller than the initial target material and being spatially distributed throughout a hemisphere shaped volume; and directing a second amplified light beam toward the collection of pieces to convert the pieces of target material to plasma that emits EUV light.

Implementations can include one or more of the following features.

The EUV light can be emitted from the hemisphere shaped volume in all directions.

The EUV light can be emitted from the hemisphere shaped volume isotropically.

The initial target material can include a metal, and the collection of pieces can include pieces of the metal. The metal can be tin.

The hemisphere shaped volume can define a longitudinal axis along a direction that is parallel to a direction of propagation of the second amplified light beam and a transverse axis along a direction that is transverse to the direction of propagation of the second amplified light beam, and directing the second amplified light beam toward the collection of pieces can include penetrating into the hemisphere shaped volume along the longitudinal axis. The majority of the pieces in the collection of pieces can be converted to plasma.

The first amplified light beam can be a pulse of light having a duration of 150 ps and a wavelength of 1 μm.

The first amplified light beam can be a pulse of light having a duration of less than 150 ps and a wavelength of 1 μm.

The first amplified light beam can include two pulses of light that are temporally separated from each other. The two pulses can include a first pulse of light and a second pulse of light, the first pulse of light having a duration of 1 ns to 10 ns, and the second pulse of light having a duration of less than 1 ns.

The first and second amplified light beams can be beams of pulses.

The first amplified light beam can have an energy that is insufficient to convert the target material to plasma, and the second amplified light beam have an energy that is sufficient to convert the target material to plasma.

A density of the pieces of target material can increase along a direction that is parallel to a direction of propagation of the second amplified light beam.

The pieces of target material in the hemisphere shaped volume can have a diameter of 1-10 μm.

In another general aspect, a target system for an extreme ultraviolet (EUV) light source includes pieces of a target material distributed throughout a hemisphere shaped volume, the target material including a material that emits EUV light when converted to plasma; and a plane surface adjacent to the hemisphere shaped volume and defining a front boundary of the hemisphere shaped volume, the front boundary being positioned to face a source of an amplified light beam. The hemisphere shaped volume faces away from the source of the amplified light beam.

Implementations can include one or more of the following features. The hemisphere shaped volume can have a cross-sectional diameter in a direction that is transverse to a direction of propagation of the amplified light beam, and a maximum of the cross-sectional diameter can be at the plane surface.

A density of the pieces of the target material in the hemisphere shaped volume can increase along a direction that is parallel to a direction of propagation of the amplified light beam.

At least some of the pieces can be individual pieces that are physically separated from each other.

The hemisphere shaped volume can be irradiated with an amplified light beam having sufficient energy to convert the individual pieces of the target material to plasma, and the hemisphere shaped target can emit EUV light in all directions.

The target material droplet can be part of a stream of target material droplets that are released from a nozzle, and the target system also can include a second target material droplet that is separate from the target material droplet and released from the nozzle after the target material droplet. The target system also can include the nozzle.

The source of the amplified light beam can be an opening in a chamber that receives the target material droplet.

In another general aspect, an extreme ultraviolet (EUV) light source includes a first source that produces a pulse of light; a second source that produces an amplified light beam; a target material delivery system; a chamber coupled to the target material delivery system; and a steering system that steers the amplified light beam toward a target location in the chamber that receives a target material droplet from the target material delivery system, the target material droplet including a material that emits EUV light after being converted to plasma. The target material droplet forms a target when struck by the pulse of light, the target including a hemisphere shaped volume having pieces of the target material throughout the volume, and a plane surface positioned between the hemisphere shaped volume and the second source.

Implementations can include the following feature. The pulse of light can be 150 ps or less in duration.

Implementations of any of the techniques described above may include a method, a process, a target, an assembly for generating a hemisphere shaped target, a device for generating a hemisphere shaped target, a kit or pre-assembled system for retrofitting an existing EUV light source, or an apparatus. The details of one or more implementations are set forth in the accompanying drawings and the description below. Other features will be apparent from the description and drawings, and from the claims.

DRAWING DESCRIPTION

FIG. **1**A is a perspective view of an exemplary hemisphere shaped target for an EUV light source.

FIG. **1**B is a side view of the exemplary hemisphere shaped target of FIG. **1**A.

FIG. **1**C is a front cross-sectional view of the exemplary hemisphere shaped target of FIG. **1**A along the line **1**C-**1**C.

FIG. **1**D is a plot of an exemplary density as a function of location within the hemisphere shaped target of FIG. **1**A.

FIG. **2**A is a block diagram of an exemplary laser produced plasma extreme ultraviolet light source.

FIG. **2**B is a block diagram of an example of a drive laser system that can be used in the light source of FIG. **2**A.

FIG. **3**A is a top plan view of another laser produced plasma extreme ultraviolet (EUV) light source and a lithography tool coupled to the EUV light source.

FIGS. **3**B and **3**C are top views of a vacuum chamber of the EUV light source of FIG. **3**A at two different times.

FIG. **3**D is a partial side perspective view of the EUV light source of FIG. **3**A.

FIG. **3**E is a cross-sectional plan view of the EUV light source of FIG. **3**D taken along the line **3**E-**3**E.

FIG. **4** is a flow chart of an exemplary process for forming a hemisphere shaped target.

FIG. **5** is a plot of an exemplary waveform for transforming a target material droplet into a hemisphere shaped target.

FIGS. **6**A-**6**D are side views of a target material droplet transforming into a hemisphere shaped target through interactions with the waveform of FIG. **5**.

FIGS. **7**A and **7**B are plots of exemplary density profiles as a function of spatial location.

FIGS. **8**A and **8**B are plots of the target size, which shows the spatial extent of a hemisphere shaped target, as a function of time.

FIG. **9** is a plot of another exemplary waveform for transforming a target material droplet into a hemisphere shaped target.

FIGS. **10**A-**10**E are side views of a target material droplet transforming into a hemisphere shaped target through interactions with the waveform of FIG. **9**.

FIGS. **11**A-**11**C are plots of exemplary density profiles as a function of spatial location.

DESCRIPTION

Referring to FIG. **1**A, a perspective view of an exemplary target **5** is shown. The hemisphere shape and gently sloped density profile of the target **5** enables the target **5** to provide additional EUV light, increased conversion efficiency, and EUV light that is radially emitted outward from the target in all directions. The hemisphere shape can be a half of a sphere or any other portion of a sphere. However, the hemisphere shape can take other forms. For example, the hemisphere shape can be a partial oblate or prolate spheroid.

The target **5** can be used in a laser produced plasma (LPP) extreme ultraviolet (EUV) light source. The target **5** includes a target material that emits EUV light when in a plasma state. The target material can be a target mixture that includes a target substance and impurities such as non-target particles. The target substance is the substance that is converted to a plasma state that has an emission line in the EUV range. The target substance can be, for example, a droplet of liquid or molten metal, a portion of a liquid stream, solid particles or clusters, solid particles contained within liquid droplets, a foam of target material, or solid particles contained within a portion of a liquid stream. The target substance, can be, for example, water, tin, lithium, xenon, or any material that, when converted to a plasma state, has an emission line in the EUV range. For example, the target substance can be the element tin, which can be used as pure tin (Sn); as a tin compound, for example, $SnBr_4$, $SnBr_2$, SnH_4; as a tin alloy, for example, tin-gallium alloys, tin-indium alloys, tin-indium-gallium alloys, or any combination of these alloys. Moreover, in the situation in which there are no impurities, the target material includes only the target substance. The discussion below provides examples in which the target material is a target material droplet made of molten metal. In these examples, the target material is referred to as the target material droplet. However, the target material can take other forms.

Irradiating the target material with an amplified light beam of sufficient energy (a "main pulse" or a "main beam") converts the target material to plasma, thereby causing the target **5** to emit EUV light. FIG. **1**B is a side view of the target **5**. FIG. **1**C is a front cross-sectional view of the target **5** along the line **1**C-**1**C of FIG. **1**A.

The target **5** is a collection of pieces of target material **20** distributed in a hemisphere shaped volume **10**. The target **5** is formed by striking a target material with one or more pulses of radiation (a "pre-pulse") that precede (in time) the main pulse to transform the target material into a collection of pieces of target material. The pre-pulse is incident on a surface of the target material and the interaction between the initial leading edge of the pre-pulse and the target material can produce a plasma (that does not necessarily emit EUV light) at the surface of the target material. The pre-pulse continues to be incident on the created plasma and is absorbed by the plasma over a period that is similar to the temporal duration of the pre-pulse, about 150 picoseconds (ps). The created plasma expands as time passes. An interaction between the expanding plasma and the remaining portion of the target material can generate a shock wave that can act on the target material non-uniformly, with the center of the target material receiving the brunt of the shock wave.

The shock wave can cause the center part of the target material to break into particles that expand in three dimensions. However, because the center part also experiences force in an opposite direction from the expanding plasma, a hemisphere of particles can be formed instead of a sphere.

The pieces of target material **20** in the collection can be non-ionized pieces or segments of target material. That is, the pieces of target material **20** are not in a plasma state when the main pulse strikes the target **5**. The pieces or segments of target material **20** can be, for example, a mist of nano- or micro-particles, separate pieces or segments of molten metal, or a cloud of atomic vapor. The pieces of target material **20** are bits of material that are distributed in a hemisphere shaped volume, but the pieces of target material **20** are not formed as a single piece that fills the hemisphere shaped volume. There can be voids between the pieces of target material **20**. The pieces of target material **20** can also include non-target material, such as impurities, that are not converted to EUV light emitting plasma. The pieces of target material **20** are referred to as the particles **20**. Individual particles **20** can be 1-10 μm in diameter. The particles **20** can be separated from each other. Some or all of the particles **20** can have physical contact with another particle.

The hemisphere shaped volume **10** has a plane surface **12** that defines a front boundary of the hemisphere shaped volume **10**, and a hemisphere shaped portion **14** that extends away from the plane surface in a direction "z." When used in a EUV light source, a normal **15** of the plane surface **12** faces an oncoming amplified light beam **18** that propagates in the "z" direction. The plane surface **12** can be transverse to direction of propagation of the oncoming amplified light beam **18**, as shown in FIGS. **1**A and **1**B, or the plane surface **12** can be angled relative to the oncoming beam **18**.

Referring also to FIG. **1**D, the particles **20** are distributed in the hemisphere shaped volume **10** with an exemplary density gradient **25** that has a minimum at the plane surface **12** of the target **5**. The density gradient **25** is a measure of the density of particles in a unit volume as a function of position within the hemisphere shaped volume **10**. The density gradient **25** increases within the target **5** in the direction of propagation ("z") of the main pulse, and the maximum density is on a side of the target **5** opposite from the side of the plane surface **12**. The placement of the minimum density at the plane surface **12** and the gradual increase in the density of the particles **20** results in more of the main pulse being absorbed by the target **5**, thereby producing more EUV light and providing a higher conversion efficiency (CE) for a light source that uses the target **5**. In effect, this means that enough energy is provided to the target **5** by the main pulse to ionize the target **5** efficiently to produce ionized gas. Having the minimum density at or near the plane surface **12** can increase the absorption of main beam by the target **5** in at least two ways.

First, the minimum density of the target **5** is lower than the density of a target that is a continuous piece of target material (such as a target material droplet made of molten tin or a disk shaped target of molten tin). Second, the density gradient **25** places the lowest density portions of the target **5** at the plane surface **12**, which is the plane where the amplified light beam **18** enters the target **5**. Because the density of the particles **20** increases in the "z" direction, most, or all, of the amplified light beam **18** is absorbed by particles **20** that are closer to the plane surface **12** before the beam **18** reaches and is reflected from a region of high density within the target **5**. Therefore, compared to a target that has a region of high density closer to the point of impact with the amplified light beam **18**, the target **5** absorbs a higher portion of the energy in the amplified light beam **18**. The absorbed light beam **18** is used to convert the particles **20** to plasma by ionization. Thus, the density gradient **25** also enables more EUV light to be generated.

Second, the target **5** presents a larger area or volume of particles to the main pulse, enabling increased interaction between the particles **20** and the main pulse. Referring to FIGS. **1**B and **1**C, the target **5** defines a length **30** and a cross-section width **32**. The length **30** is the distance in the "z" direction along which the hemisphere portion **14** extends. The length **30** is longer than a similar length in a target that is a continuous piece of target material because the hemisphere shaped volume **10** has a longer extent in the "z" direction. A continuous piece of target material is one that has a uniform, or nearly uniform, density in the direction of propagation of the amplified light beam **18**. Additionally, because of the gradient **25**, the amplified light beam **18** propagates further into the target **5** in the "z" direction while reflections are kept low. The relatively longer length **30** provides a longer plasma scale length. The plasma scale length for the target **5** can be, for example, 200 μm, which can be twice the value of the plasma scale length for a disk shaped target made from a continuous piece of target material. A longer plasma scale length allows more of the amplified light beam **18** to be absorbed by the target **5**.

The cross-section width **32** is the width of the plane surface **12** of the target **5**. The cross-section interaction width **32** can be, for example, about 200 μm, when the target **5** is generated with a pre-pulse that occurs 1000 ns prior to the main pulse, and the pre-pulse has a duration of 150 ps and a wavelength of 1 μm. The cross-section interaction width **32** can be about 300 μm when the target **5** is generated with a 50 ns duration CO_2 laser pulse. A pulse of light or radiation has a temporal duration for an amount of time during which a single pulse has an intensity of 50% or more of the maximum intensity of the pulse. This duration can also be referred to as the full width at half maximum (FWHM).

Like the length **30**, the cross-section width **32** is larger than a similar dimension in a target that is made of a continuous, coalesced piece of target material (such as a target material droplet made of coalesced molten metal). Because both the interaction length **30** and the interaction width **32** are relatively larger than other targets, the target **5** also has a larger EUV light emitting volume. The light emitting volume is the volume in which the particles **20** are distributed and can be irradiated by the amplified light beam **18**. For example, the target **5** can have a light emitting volume that is twice that of a disk shaped target of molten metal. The larger light emitting volume of the target **5** results in generation of greater amounts of EUV light and a higher conversion efficiency (CE) because a higher portion of the target material (the particles **20**) in the target **5** is presented to and irradiated by the amplified light beam **18** and subsequently converted to plasma.

Further, the target **5** does not have a wall or high density region at a back side **4** that could prevent EUV light from being emitted in the direction of propagation of the main pulse. Thus, the target **5** emits EUV radially outward in all directions, allowing more EUV light to be collected and further increasing the collection efficiency. Moreover, radially isotropic EUV light or substantially isotropic EUV light can provide improved performance for a lithography tool (not shown) that uses the EUV light emitted from the target **5** by reducing the amount of calibration needed for the tool. For example, if uncorrected, unexpected spatial variations in

EUV intensity can cause overexposure to a wafer imaged by the lithography tool. The target **5** can minimize such calibration concerns by emitting EUV light uniformly in all directions. Moreover, because the EUV light is radially uniform, errors in alignment and fluctuations in alignment within the lithography tool or upstream from the lithography tool do not also cause variations in intensity.

FIGS. **2**A, **2**B, and **3**A-**3**C show exemplary LPP EUV light sources in which the target **5** can be used.

Referring to FIG. **2**A, an LPP EUV light source **100** is formed by irradiating a target mixture **114** at a target location **105** with an amplified light beam **110** that travels along a beam path toward the target mixture **114**. The target location **105**, which is also referred to as the irradiation site, is within an interior **107** of a vacuum chamber **130**. When the amplified light beam **110** strikes the target mixture **114**, a target material within the target mixture **114** is converted into a plasma state that has an element with an emission line in the EUV range to produce EUV light **106**. The created plasma has certain characteristics that depend on the composition of the target material within the target mixture **114**. These characteristics can include the wavelength of the EUV light produced by the plasma and the type and amount of debris released from the plasma.

The light source **100** also includes a target material delivery system **125** that delivers, controls, and directs the target mixture **114** in the form of liquid droplets, a liquid stream, solid particles or clusters, solid particles contained within liquid droplets or solid particles contained within a liquid stream. The target mixture **114** can also include impurities such as non-target particles. The target mixture **114** is delivered by the target material delivery system **125** into the interior **107** of the chamber **130** and to the target location **105**.

The light source **100** includes a drive laser system **115** that produces the amplified light beam **110** due to a population inversion within the gain medium or mediums of the laser system **115**. The light source **100** includes a beam delivery system between the laser system **115** and the target location **105**, the beam delivery system including a beam transport system **120** and a focus assembly **122**. The beam transport system **120** receives the amplified light beam **110** from the laser system **115**, and steers and modifies the amplified light beam **110** as needed and outputs the amplified light beam **110** to the focus assembly **122**. The focus assembly **122** receives the amplified light beam **110** and focuses the beam **110** to the target location **105**.

In some implementations, the laser system **115** can include one or more optical amplifiers, lasers, and/or lamps for providing one or more main pulses and, in some cases, one or more pre-pulses. Each optical amplifier includes a gain medium capable of optically amplifying the desired wavelength at a high gain, an excitation source, and internal optics. The optical amplifier may or may not have laser mirrors or other feedback devices that form a laser cavity. Thus, the laser system **115** produces an amplified light beam **110** due to the population inversion in the gain media of the laser amplifiers even if there is no laser cavity. Moreover, the laser system **115** can produce an amplified light beam **110** that is a coherent laser beam if there is a laser cavity to provide enough feedback to the laser system **115**. The term "amplified light beam" encompasses one or more of: light from the laser system **115** that is merely amplified but not necessarily a coherent laser oscillation and light from the laser system **115** that is amplified (externally or within a gain medium in the oscillator) and is also a coherent laser oscillation.

The optical amplifiers in the laser system **115** can include as a gain medium a filling gas that includes CO_2 and can amplify light at a wavelength of between about 9100 and about 11000 nm, and in particular, at about 10.6 μm, at a gain greater than or equal to 1000. In some examples, the optical amplifiers amplify light at a wavelength of 10.59 μm. Suitable amplifiers and lasers for use in the laser system **115** can include a pulsed laser device, for example, a pulsed, gas-discharge CO_2 laser device producing radiation at about 9300 nm or about 10600 nm, for example, with DC or RF excitation, operating at relatively high power, for example, 10 kW or higher and high pulse repetition rate, for example, 50 kHz or more. The optical amplifiers in the laser system **115** can also include a cooling system such as water that can be used when operating the laser system **115** at higher powers.

FIG. **2**B shows a block diagram of an example drive laser system **180**. The drive laser system **180** can be used as the drive laser system **115** in the source **100**. The drive laser system **180** includes three power amplifiers **181**, **182**, and **183**. Any or all of the power amplifiers **181**, **182**, and **183** can include internal optical elements (not shown). The power amplifiers **181**, **182**, and **183** each include a gain medium in which amplification occurs when pumped with an external electrical or optical source.

Light **184** exits from the power amplifier **181** through an output window **185** and is reflected off a curved mirror **186**. After reflection, the light **184** passes through a spatial filter **187**, is reflected off of a curved mirror **188**, and enters the power amplifier **182** through an input window **189**. The light **184** is amplified in the power amplifier **182** and redirected out of the power amplifier **182** through an output window **190** as light **191**. The light **191** is directed toward the amplifier **183** with fold mirrors **192** and enters the amplifier **183** through an input window **193**. The amplifier **183** amplifies the light **191** and directs the light **191** out of the amplifier **183** through an output window **194** as an output beam **195**. A fold mirror **196** directs the output beam **195** upwards (out of the page) and toward the beam transport system **120**.

The spatial filter **187** defines an aperture **197**, which can be, for example, a circular opening through which the light **184** passes. The curved mirrors **186** and **188** can be, for example, off-axis parabola mirrors with focal lengths of about 1.7 m and 2.3 m, respectively. The spatial filter **187** can be positioned such that the aperture **197** coincides with a focal point of the drive laser system **180**. The example of FIG. **2**B shows three power amplifiers. However, more or fewer power amplifiers can be used.

Referring again to FIG. **2**A, the light source **100** includes a collector mirror **135** having an aperture **140** to allow the amplified light beam **110** to pass through and reach the target location **105**. The collector mirror **135** can be, for example, an ellipsoidal mirror that has a primary focus at the target location **105** and a secondary focus at an intermediate location **145** (also called an intermediate focus) where the EUV light can be output from the light source **100** and can be input to, for example, an integrated circuit beam positioning system tool (not shown). The light source **100** can also include an open-ended, hollow conical shroud **150** (for example, a gas cone) that tapers toward the target location **105** from the collector mirror **135** to reduce the amount of plasma-generated debris that enters the focus assembly **122** and/or the beam transport system **120** while allowing the amplified light beam **110** to reach the target location **105**. For this purpose, a gas flow can be provided in the shroud that is directed toward the target location **105**.

The light source **100** can also include a master controller **155** that is connected to a droplet position detection feedback system **156**, a laser control system **157**, and a beam control system **158**. The light source **100** can include one or more target or droplet imagers **160** that provide an output indicative of the position of a droplet, for example, relative to the target location **105** and provide this output to the droplet position detection feedback system **156**, which can, for example, compute a droplet position and trajectory from which a droplet position error can be computed either on a droplet by droplet basis or on average. The droplet position detection feedback system **156** thus provides the droplet position error as an input to the master controller **155**. The master controller **155** can therefore provide a laser position, direction, and timing correction signal, for example, to the laser control system **157** that can be used, for example, to control the laser timing circuit and/or to the beam control system **158** to control an amplified light beam position and shaping of the beam transport system **120** to change the location and/or focal power of the beam focal spot within the chamber **130**.

The target material delivery system **125** includes a target material delivery control system **126** that is operable in response to a signal from the master controller **155**, for example, to modify the release point of the droplets as released by a target material supply apparatus **127** to correct for errors in the droplets arriving at the desired target location **105**.

Additionally, the light source **100** can include a light source detector **165** that measures one or more EUV light parameters, including but not limited to, pulse energy, energy distribution as a function of wavelength, energy within a particular band of wavelengths, energy outside of a particular band of wavelengths, and angular distribution of EUV intensity and/or average power. The light source detector **165** generates a feedback signal for use by the master controller **155**. The feedback signal can be, for example, indicative of the errors in parameters such as the timing and focus of the laser pulses to properly intercept the droplets in the right place and time for effective and efficient EUV light production.

The light source **100** can also include a guide laser **175** that can be used to align various sections of the light source **100** or to assist in steering the amplified light beam **110** to the target location **105**. In connection with the guide laser **175**, the light source **100** includes a metrology system **124** that is placed within the focus assembly **122** to sample a portion of light from the guide laser **175** and the amplified light beam **110**. In other implementations, the metrology system **124** is placed within the beam transport system **120**. The metrology system **124** can include an optical element that samples or re-directs a subset of the light, such optical element being made out of any material that can withstand the powers of the guide laser beam and the amplified light beam **110**. A beam analysis system is formed from the metrology system **124** and the master controller **155** since the master controller **155** analyzes the sampled light from the guide laser **175** and uses this information to adjust components within the focus assembly **122** through the beam control system **158**.

Thus, in summary, the light source **100** produces an amplified light beam **110** that is directed along the beam path to irradiate the target mixture **114** at the target location **105** to convert the target material within the mixture **114** into plasma that emits light in the EUV range. The amplified light beam **110** operates at a particular wavelength (that is also referred to as a source wavelength) that is determined based on the design and properties of the laser system **115**. Additionally, the amplified light beam **110** can be a laser beam when the target material provides enough feedback back into the laser system **115** to produce coherent laser light or if the drive laser system **115** includes suitable optical feedback to form a laser cavity.

Referring to FIG. **3**A, a top plan view of an exemplary optical imaging system **300** is shown. The optical imaging system **300** includes an LPP EUV light source **305** that provides EUV light to a lithography tool **310**. The light source **305** can be similar to, and/or include some or all of the components of, the light source **100** of FIGS. **2**A and **2**B. As discussed below, the target **5** can be used in the light source **305** to increase the amount of light emitted by the light source **305**.

The light source **305** includes a drive laser system **315**, an optical element **322**, a pre-pulse source **324**, a focusing assembly **326**, a vacuum chamber **340**, and an EUV collecting optic **346**. The EUV collecting optic **346** directs the EUV light emitted by converting the target **5** to plasma to the lithography tool **310**. The EUV collection optic **346** can be the mirror **135** (FIG. **2**A).

Referring also to FIGS. **3**B-**3**E, the light source **305** also includes a target material delivery apparatus **347** that produces a stream of target material **348**. The stream of target material **348** can include target material in any form, such as liquid droplets, a liquid stream, solid particles or clusters, solid particles contained within liquid droplets or solid particles contained within a liquid stream. In the discussion below, the target material stream **348** includes target material droplets **348**. In other examples, the target material stream can include target material of other forms.

The target material droplets travel along the “x” direction from the target material delivery apparatus **347** to a target location **342** in the vacuum chamber **340**. The drive laser system **315** produces an amplified light beam **316**. The amplified light beam **316** can be similar to the amplified light beam **18** of FIGS. **1**A-**1**C, or the amplified light beam **110** of FIGS. **2**A and **2**B, and can be referred to as a main pulse or a main beam. The amplified light beam **316** has an energy sufficient to convert the particles **20** in the target **5** into plasma that emits EUV light.

In some implementations, the drive laser system **315** can be a dual-stage master oscillator and power amplifier (MOPA) system that uses carbon dioxide (CO_2) amplifiers within the master oscillator and power amplifier, and the amplified light beam **316** can be a 130 ns duration, 10.6 μm wavelength CO_2 laser light pulse generated by the MOPA. In other implementations, the amplified light beam **316** can be a CO_2 laser light pulse that has a duration of less than 50 ns.

The pre-pulse source **324** emits a pulse of radiation **317**. The pre-pulse source **324** can be, for example, a Q-switched Nd:YAG laser, and the pulse of radiation **317** can be a pulse from the Nd.YAG laser. The pulse of radiation **317** can have a duration of 10 ns and a wavelength of 1.06 μm, for example.

In the example shown in FIG. **3**A, the drive laser system **315** and the pre-pulse source **324** are separate sources. In other implementations, they can be a part of the same source. For example, both the pulse of radiation **317** and the amplified light beam **316** can be generated by the drive laser system **315**. In such an implementation, the drive laser system **315** can include two CO_2 seed laser subsystems and one amplifier. One of the seed laser subsystems can produce an amplified light beam having a wavelength of 10.26 μm, and the other seed laser subsystem can produce an amplified light beam having a wavelength of 10.59 μm. These two wavelengths can come from different lines of the CO_2 laser. Both amplified light beams from the two seed laser subsystems are amplified in the same power amplifier chain and then angularly dispersed to reach different locations within the chamber **340**. In one example, the amplified light beam with the wavelength of 10.26 μm is used as the pre-pulse **317**, and the amplified light beam with the wavelength of 10.59 μm is used as the amplified light beam **316**. In other examples, other lines of the CO_2 laser, which can generate different wavelengths, can be used to generate the two amplified light beams (one of which is the pulse of radiation **317** and the other of which is the amplified light beam **316**).

Referring again to FIG. **3**A, the optical element **322** directs the amplified light beam **316** and the pulse of radiation **317** from the pre-pulse source **324** to the chamber **340**. The optical element **322** is any element that can direct the amplified light beam **316** and the pulse of radiation **317** along similar paths and deliver the amplified light beam **316** and the pulse of radiation **317** to the chamber **340**. In the example shown in FIG. **3**A, the optical element **322** is a dichroic beamsplitter that receives the amplified light beam **316** and reflects it toward the chamber **340**. The optical element **322** receives the pulse of radiation **317** and transmits the pulses toward the chamber **340**. The dichroic beamsplitter has a coating that reflects the wavelength(s) of the amplified light beam **316** and transmits the wavelength(s) of the pulse of radiation **317**. The dichroic beamsplitter can be made of, for example, diamond.

In other implementations, the optical element **322** is a mirror that defines an aperture (not shown). In this implementation, the amplified light beam **316** is reflected from the mirror surface and directed toward the chamber **340**, and the pulses of radiation pass through the aperture and propagate toward the chamber **340**.

In still other implementations, a wedge-shaped optic (for example, a prism) can be used to separate the main pulse **316**, the pre-pulse **317**, and the pre-pulse **318** into different angles, according to their wavelengths. The wedge-shaped optic can be used in addition to the optical element **322**, or it can be used as the optical element **322**. The wedge-shaped optic can be positioned just upstream (in the "−z" direction) of the focusing assembly **326**.

Additionally, the pulse of radiation **317** can be delivered to the chamber **340** in other ways. For example, the pulse **317** can travel through optical fibers that deliver the pulses **317** and **318** to the chamber **340** and/or the focusing assembly **326** without the use of the optical element **322** or other directing elements. In these implementations, the fiber can bring the pulse of radiation **317** directly to an interior of the chamber **340** through an opening formed in a wall of the chamber **340**.

Regardless of how the amplified light beam **316** and the pulses of radiation **317** and **318** are directed toward the chamber **340**, the amplified light beam **316** is directed to a target location **342** in the chamber **340**. The pulse of radiation **317** is directed to a location **341**. The location **341** is displaced from the target location **342** in the "−x" direction.

The amplified light beam **316** from the drive laser system **315** is reflected by the optical element **322** and propagates through the focusing assembly **326**. The focusing assembly **326** focuses the amplified light beam **316** onto the target location **342**. The pulse of radiation **317** from the pre-pulse source **324** passes through the optical element **322** and through the focusing assembly **216** to the chamber **340**. The pulse of radiation **317** propagates to the location **341** in the chamber **340** that is in the "−x" direction relative to the target location **342**. The displacement between the location **342** and the location **341** allows the pulse of radiation **317** to irradiate a target material droplet to convert the droplet to the hemisphere shaped target **5** before the target **5** reaches the target location **342** without substantially ionizing the target **5**. In this manner, the hemisphere shaped target **5** can be a pre-formed target that is formed at a time before the target **5** enters the target location **342**.

In greater detail and referring also to FIGS. **3**B and **3**C, the target location **342** is a location inside of the chamber **340** that receives the amplified light beam **316** and a droplet in the stream of target material droplets **348**. The target location **342** is also a location that is positioned to maximize an amount of EUV light delivered to the EUV collecting optic **346**. For example, the target location **342** can be at a focal point of the EUV collecting optic **346**. FIGS. **3**B and **3**C show top views of the chamber **340** at times t_1 and t_2, respectively, with time=t_1 occurring before time=t_2. In the example shown in FIGS. **3**B and **3**C, the amplified light beam **316** and the pulsed beam of radiation **317** occur at different times and are directed toward different locations within the chamber **340**.

The stream **348** travels in the "x" direction from the target material supply apparatus **347** to the target location **342**. The stream of target material droplets **348** includes the target material droplets **348*a***, **348*b***, and **348*c***. At a time=t_1 (FIG. **3**B), the target material droplets **348*a*** and **348*b*** travel in the "x" direction from the target material supply apparatus **347** to the target location **342**. The pulsed beam of radiation **317** irradiates the target material droplet **348*a*** at the time "t_1" at the location **341**, which is displaced in the "−x" direction from the target location **342**. The pulsed beam of radiation **317** transforms the target material droplet **348*b*** into the hemisphere target **5**. At the time=t_2 (FIG. **3**C), the amplified light beam **316** irradiates the target **5** and converts the particles **20** of target material into EUV light.

Referring to FIG. **4**, an exemplary process **400** for generating the hemisphere shaped target **5** is shown. The process **400** can be performed using the target material supply apparatus **127** (FIG. **2**A) or the target material supply apparatus **347** (FIGS. **3**B-**3**E).

An initial target material is released toward a target location (**410**). Referring also to FIGS. **3**B and **3**C, the target material droplet **348*a*** is released from the target material supply apparatus **347** and travels toward the target location **342**. The initial target material is a target material droplet that emerges or is released from the target material supply apparatus **347** as a droplet. The initial target material droplet is a droplet that has not been transformed or altered by a pre-pulse. The initial target material droplet can be a coalesced sphere or substantially spherical piece of molten metal that can be considered as a continuous piece of target material. The target material droplet **348*a*** prior to the time "t_1" is an example of an initial target material in this example.

A first amplified light beam is directed toward the initial target material to generate a collection of pieces of target material distributed in a hemisphere shaped volume (**420**) without substantially ionizing the initial target material. The collection of pieces of target material can be the particles **20** (FIGS. **1**A-**1**C), which are distributed in the hemisphere shaped volume **10**. The first amplified light beam can be the pulsed light beam **317** emitted from the source **324** (FIGS. **3**A, **3**D, and **3**E). The first amplified light beam can be referred to as the "pre-pulse." The first amplified light beam is a pulse of light that has an energy and/or pulse duration sufficient to transform the target material droplet **348*a*** from a droplet that is a continuous or coalesced segment or piece of molten target material into the target **5**, which is a hemisphere shaped distribution of particles **20**.

The first amplified light beam can be, for example, a pulse of light that has a duration of 130 ns and a wavelength of 1 μm. In another example, first amplified light beam can be a pulse of light that has a duration of 150 ps, a wavelength of 1 μm, an energy of 10 milliJoules (mJ), a 60 μm focal spot, and an intensity of 2×10^{12} W/cm^2. The energy, wavelength, and/or duration of the first amplified light beam are selected to transform the target material droplet into the hemisphere shaped target **5**. In some implementations, the first amplified light beam includes more than one pulse. For example, the first amplified light beam can include two pulses, separated from each other in time, and having different energies and durations. FIG. **9** shows an example in which the first amplified light beam includes more than one pulse. Further, the first amplified light beam can be a single pulse that has a shape (energy or intensity as a function of time) to provide an effect that is similar to that achieved by multiple pre-pulses. The second amplified light beam has energy sufficient to convert the target material droplet into a collection of pieces.

A second amplified light beam is directed toward the collection of pieces to convert the particles **20** to plasma that emits EUV light (**430**). The second amplified light beam can be referred to as the "main pulse." The amplified light beam **316** of FIG. **3**A is an example of a second amplified light beam. The amplified light beam **316** has sufficient energy to convert all or most of the particles **20** of the target **5** into plasma that emits EUV light.

Referring to FIG. **5**, an example of a waveform **500** that can be used to transform a target material droplet into a hemisphere shaped target is shown. FIG. **5** shows the amplitude of the waveform **500** as a function of time. The waveform **500** shows a representation of the collection of amplified light beams that strike a particular target material droplet in a single cycle of operation of the EUV light source. A cycle of operation is a cycle that emits a pulse or burst of EUV light. The waveform **500** also can be referred to as a laser train **500** or a pulse train **500**. In the waveform **500**, the collection of amplified light beams includes a pre-pulse **502** and a main pulse **504**.

The pre-pulse **502** begins at time t=0, and the main pulse **504** begins at a time t=1000 ns. In other words, the main pulse **504** occurs 1000 ns after the pre-pulse **502**. In the waveform **500**, the pre-pulse **502** can have a wavelength of 1.0 μm, a duration of 150 ps, an energy of 10 mJ, a focal spot 60 μm in diameter, and an intensity of 2×10^{12} W/cm^2. This is an example of one implementation of the waveform **500**. Other parameter values can be used, and the parameter values of the pre-pulse **502** can vary by a factor of 5 as compared to this example. For example, in some implementations, the pre-pulse **502** can have a duration of 5-20 ps, and an energy of 1-20 mJ. The main pulse **504** can have a wavelength of 5-11 μm, a pulse duration of 15-200 ns, a focus spot size of 50-300 μm, and an intensity of 3×10^9 to 8×10^{10} W/cm^2. For example, the main pulse **504** can have a wavelength of 10.59 μm and a pulse duration of 130 ns. In another example, the main pulse can have a wavelength of 10.59 μm and a pulse duration of 50 ns or less.

In addition to the times t=0 and t=1000 ns, the times t_1-t_4 are also shown on the time axis. The time t_1 is shortly before the pre-pulse **502** occurs. The time t_2 is after the pre-pulse **502** ends and before the main pulse **504** begins. The time t**3** occurs shortly before the main pulse **504**, and the time t**4** occurs after the main pulse **504**. The times t_1-t_4 are used in the discussion below, with respect to FIGS. **6**A-**6**D, of a transformation of a target material droplet to a hemisphere shaped target using the waveform **500**.

Although the waveform **500** is shown as a continuous waveform in time, the pre-pulse **502** and main pulse **504** that make up the waveform **500** can be generated by different sources. For example, the pre-pulse **502** can be a pulse of light generated by the pre-pulse source **324**, and the main pulse **504** can be generated by the drive laser system **315**. When the pre-pulse **502** and the main pulse **504** are generated by separate sources that are in different locations relative to the chamber **340** (FIG. **3**A), the pre-pulse **502** and the main pulse **504** can be directed to the chamber **340** with the optical element **322**.

Referring also to FIGS. **6**A-**6**D, interactions between a target material droplet **610** and the waveform **500** that transform the target material droplet **610** into a hemisphere shaped target **614** are shown. A target supply apparatus **620** releases a stream of target material droplets **622** from an orifice **624**. The target material droplets **622** travel in the "x" direction toward a target location **626**. FIGS. **6**A-**6**D show the target supply apparatus **620** and the droplet stream **622** at the times $t=t_1$, $t=t_2$, $t=t_3$, and $t=t_4$, respectively. FIG. **5** also shows the times $t=t_1$ through $t=t_4$ relative to the waveform **500**.

Referring to FIG. **6**A, the pre-pulse **502** approaches the target material droplet **610**. The target material droplet **610** is a droplet of target material. The target material can be molten metal, such as molten tin. The target material droplet **610** is a continuous segment or piece of target material that has a uniform density in the "z" direction (the direction of propagation of the waveform **500**). The cross-sectional size of a target material droplet can be, for example, between 20-40 μm. FIG. **7**A shows the density of the target material droplet **610** as a function of position along the "z" direction. As shown in FIG. **7**A, compared to free space, the target material droplet **610** presents a steep increase in density to the waveform **500**.

The interaction between the pre-pulse **502** and the target material droplet **610** forms a collection of pieces of target material **612** that are arranged in a geometric distribution. The pieces of target material **612** are distributed in a hemisphere shaped volume that extends outward from a plane surface **613** in the "x" and "z" direction. The pieces of target material **612** can be a mist of nano- or micro-particles, separate pieces of molten metal, or a cloud of atomic vapor. The pieces of target material can be 1-10 μm in diameter.

A purpose of the interaction between the pre-pulse **502** and the target material droplet **610** is to form a target that has a spatial extent that is larger than the diameter of the main pulse **504** but without substantially ionizing the target. In this manner, as compared to a smaller target, the created target presents more target material to the main beam and can use more of the energy in the main pulse **504**. The pieces of target material **612** have a spatial extent in the x-y and x-z planes that is larger than the extent of the target material droplet **610** in the x-y and x-z planes.

As time passes, the collection of pieces **612** travels in the "x" direction toward the target location **626**. The collection of pieces **612** also expands in the "x" and "z" directions while moving toward the target location **626**. The amount of spatial expansion depends on the duration and intensity of the pre-pulse **502**, as well as the amount of time over which the collection of pieces **612** is allowed to expand. The density of the collection of pieces **612** decreases as time passes, because the pieces spread out. A lower density generally allows an oncoming light beam to be absorbed by more of the material in a volume, and a high density can prevent or reduce the amount of light absorbed and the amount of EUV light produced. A wall of high density through which light cannot pass or be absorbed and is instead reflected is the "critical density." However, the most efficient absorption by a material can occur near but below the critical density. Thus, it can be beneficial to for the target **614** to be formed by allowing the collection of pieces **614** to expand over a finite time period that is long enough to allow the collection of pieces **613** to expand spatially without being so long that the density of the pieces decreases to a point where the efficiency of laser absorption decreases. The finite time period can be the time between the pre-pulse **502** and the main pulse **504** and can be, for example, about 1000 ns.

Referring also to FIGS. **8**A and **8**B, examples of the spatial expansion of the collection of pieces **612** as a function of time after the pre-pulse strikes a target material droplet for two different pre-pulses are shown, with FIG. **8**A showing an example for a pre-pulse similar to the pre-pulse **502**. The time after the pre-pulse strikes a target material droplet can be referred to as the delay time. FIG. **8**A shows the size of the collection of pieces **612** as a function of delay time when the pre-pulse has a wavelength of 1.0 μm, a duration of 150 ps, an energy of 10 mJ, a focal spot 60 μm in diameter, and an intensity of 2×10^{12} W/cm^2. FIG. **8**B shows the size of the collection of pieces **612** as a function of delay time when the pre-pulse has a wavelength of 1.0 μm, a duration of 150 ps, an energy of 5 mJ, a focal spot 60 μm in diameter, and an intensity of 1×10^{12} W/cm^2. Comparing FIG. **8**A to FIG. **8**B shows that the collection of pieces **612** expands more rapidly in the vertical directions (x/y) when struck by the more energetic and more intense pre-pulse of FIG. **8**A.

Referring again to, FIG. **6**C the target material droplet **610** and the stream of droplets **622** are shown at the time=t_3. At the time=t_3, the collection of target material pieces **612** has expanded into the hemisphere shaped target **614** and arrives at the target location **626**. The mail pulse **504** approaches the hemisphere shaped target **614**.

FIG. **7**B shows the density of the hemisphere shaped target **614** just before the main pulse **504** reaches the target **614**. The density is expressed as density gradient **705** that is density of particles **612** in the target **614** a function of position in the "z" direction, with z=0 being the plane surface **613**. As shown, the density is minimum at the plane surface **613** and increases in the "z" direction. Because the density is at a minimum at the plane surface **613**, and the minimum density is lower than that of the target material droplet **610**, compared to the target material droplet **610**, the main pulse **504** enters the target **614** relatively easily (less of the main pulse **504** is absorbed).

As the main beam **504** travels in the target **614**, the particles **612** absorb the energy in the main beam **504** and are converted to plasma that emits EUV light. The density of the target **614** increases in the direction of propagation "z" and can increase to an amount where the main beam **504** cannot penetrate and is instead reflected. The location in the target **614** with such a density is the critical surface (not shown). However, because the density of the target **614** is initially relatively low, a majority, most, or all, of the main beam **504** is absorbed by the particles **615** prior to reaching the critical surface. Thus, the density gradient provides a target that is favorable for EUV light generation.

Additionally, because the hemisphere shaped target **614** does not have a wall of high density, the EUV light **618** is radially emitted from the target **614** in all directions. This is unlike a disk shaped target or other target with a higher density, where the interaction between the main pulse and the target generates plasma and a shock wave that blows off some of the target as dense target material in the direction of propagation of the main pulse **504**. The blown off material reduces the amount of material available for conversion to plasma and also absorbs some of the EUV light emitted in the forward ("z") direction. As a result, the EUV light is emitted over 2π steradians, and only half of the EUV light is available for collection.

However, the hemisphere shaped target **614** allows collection of EUV light in all directions (4π steradians). After the main pulse **504** irradiates the hemisphere shaped target **614**, there is negligible or no dense target material left in the hemisphere shaped target **614**, and the EUV light **618** is able to escape the hemisphere shaped target **614** radially in all directions. In effect, there is very little matter present to block or absorb the EUV light **618** and prevent it from escaping. In some implementations, the EUV light **618** can be isotropic (uniform intensity) in all directions.

Thus, the hemisphere shaped target **614** provides additional EUV light by allowing EUV light **619**, which is generated in the forward direction, to escape the hemisphere shaped target **614**. Because the hemisphere shaped target **614** emits EUV light in all directions, a light source that uses the hemisphere shaped target **614** can have increased conversion efficiency (CE) as compared to a light source that uses a target that emits light over only 2π steradians. For example, when measured over 2π steradians, a hemisphere shaped target that is irradiated with a MOPA CO_2 main pulse having a duration of 130 ns can have a conversion efficiency of 3.2%, meaning that 3.2% of the CO_2 main pulse is converted into EUV light. When the hemisphere shaped target is irradiated with a MOPA CO_2 main pulse having a duration of 50 ns, the conversion efficiency is 5% based on measuring the EUV light emitted over 2π steradians. When the EUV light is measured over 4π steradians, the conversion efficiency is doubled because the amount of EUV light emitted from the target is doubled. Thus, the conversion efficiency for the two main pulses becomes 6.4% and 10%, respectively.

In the example of FIGS. **6**A-**6**D, the waveform **500**, which has a delay time of 1000 ns between the pre-pulse **502** and the main pulse **504**, is used to transform the target material droplet **610** into the hemisphere shaped target **614**. However, other waveforms with other delay times can be used for the transformation. For example, the delay between the pre-pulse **502** and the main pulse **504** can be between 200 ns and 1600 ns. A longer delay time provides a target with a larger spatial extent (volume) and a lower density of target material. A shorter delay time provides a target with a smaller spatial extent (volume) and a higher density of target material.

FIG. **9** shows another exemplary waveform **900** that, when applied to a target material droplet, transforms the target material droplet to a hemisphere shaped target. The waveform **900** includes a first pre-pulse **902**, a second pre-pulse **904**, and a main pulse **906**. The first pre-pulse **902** and the second pre-pulse **904** can be collectively considered as the first amplified light beam, and the main pulse **906** can be considered as the second amplified light beam. The first pre-pulse **902** occurs at time t=0, the second pre-pulse **904** occurs 200 ns later at time t=200 ns, and the main pulse **906** occurs at time t=1200 ns, 1200 ns after the first pre-pulse **902**.

In the example of FIG. **9**, the first pre-pulse **502** has a duration of 1-10 ns, and the second pre-pulse **504** has a duration of less than 1 ns. For example, the duration of the second pre-pulse **504** can be 150 ps. The first pre-pulse **502** and the second pre-pulse **504** can have a wavelength of 1 μm. The main pulse **506** can be a pulse from a CO_2 laser that has a wavelength of 10.6 μm and a duration of 130 ns or 50 ns.

FIGS. **10**A-**10**D show the waveform **900** interacting with a target material droplet **1010** to transform the target material droplet **1010** into a hemisphere shaped target **1018**. FIGS. **10**A-**10**D show times $t=t_1$ to t_4, respectively. Times $t=t_1$ to t_4 are shown relative to the waveform **900** on FIG. **9**. The time $t=t_1$ occurs just before the first pre-pulse **502**, and the time $t=t_2$ occurs just before the second pre-pulse **504**. The time $t=t_3$ occurs just before the main pulse **506**, and the time t=t**4** occurs just after the main pulse **506**.

Referring to FIG. **10**A, a target material supply apparatus **1020** releases a stream of target material droplets **1022**. The stream **1022** travels from the target material supply apparatus **1020** to a target location **1026**. The stream **1022** includes target material droplets **1010** and **1011**. The first pre-pulse **502** approaches and strikes the target material droplet **1010**. The cross-sectional size of a target material droplet can be, for example, between 20-40 μm. Referring also to FIG. **11**A, the density profile **1100** of the target material droplet **1010** is uniform in the direction of propagation "z" of the pre-pulse **502**, and the target material droplet **1010** presents a steep density transition to the pre-pulse **502**.

The interaction between the first pre-pulse **502** and the target material droplet **1010** produces a short-scale plume **1012** (FIG. **10**B) on a side of the target material droplet **1010** that faces the oncoming first pre-pulse **902**. The plume **1012** can be a cloud of particles of the target material that is formed on or adjacent to the surface of the target material droplet **1010**. As the target material droplet **1010** travels toward the target location **1026**, the target material droplet **1010** can increase in size in the vertical "x" direction and decrease in size in the "z" direction. Together, the plume **1012** and the target material droplet **1010** can be considered as an intermediate target **1014**. The intermediate target **1014** receives the second pre-pulse **504**.

Referring also to FIG. **11**B, at the time $t=t_2$, the intermediate target **1014** has a density profile **1102**. The density profile includes a density gradient **1105** that corresponds to the portion of the intermediate target **1014** that is the plume **1012**. The density gradient **1105** is minimum at a location **1013** (FIG. **10**B) where the second pre-pulse **504** initially interacts with the plume **1012**. The density gradient **1105** increases in the direction "z" until the plume **1012** ends and the target material **1010** is reached. Thus, the first pre-pulse **502** acts to create an initial density gradient that includes densities that are lower than those present in the target material droplet **1010**, thereby enabling the intermediate target **1014** to absorb the second pre-pulse **504** more readily than the target material droplet **1010**.

The second pre-pulse **504** strikes the intermediate target **1014** and generates a collection of pieces of target material **1015**. The interaction between the intermediate target **1014** and the second pre-pulse **504** generates the collection of pieces **1015**, as shown in FIG. **10**C. As time passes, the collection of pieces of target material **1015** continues to travel in the "x" direction toward the target location **1026**. The collection of pieces of target material **1015** forms a volume, and the volume increases as the pieces expand with the passage of time. Referring to FIG. **10**D, the collection of pieces expands for 1000 ns after the second pre-pulse **502** strikes the intermediate target **1014**, and the expanded collection of pieces forms the hemisphere shaped target **1018**. The hemisphere shaped target **1018** enters the target location **1016** at time t=t**4**. The hemisphere shaped target **1018** has density that is at a minimum at a surface plane **1019**, which receives the main pulse **506**, and increases in the "z" direction.

The density profile **1110** of the hemisphere shaped target **1018** at a time just before the main pulse **506** strikes the target **1018** is shown in FIG. **11**C. The hemisphere shaped target **1018** has a gentle gradient that is at a minimum at the surface plane **1019** that receives the main pulse **506**. Thus, like the hemisphere target **614**, the hemisphere target **1018** absorbs the main pulse **506** readily and emits EUV light **1030** in all directions. As compared to the hemisphere target **614**, the maximum density of the target **1018** is lower and the gradient is less steep.

Other implementations are within the scope of the following claims. For example, the shape of the target can vary from a hemisphere that has a rounded surface. The hemisphere shaped portion **14** of the hemisphere shaped target **5** can have one or more sides that are flattened instead of being rounded. In addition to, or alternatively to, being dispersed throughout the hemisphere shaped target **5**, the particles **20** can be dispersed on a surface of the hemisphere shaped target **5**.

What is claimed is:

1. An extreme ultraviolet (EUV) light source comprising:

a solid state laser configured to produce pulses of radiation, the pulses of radiation produced by the solid state laser comprising at least a first pulse of radiation;

a second optical source configured to produce pulses of radiation, the pulses of radiation produced by the second optical source comprising at least a second pulse of radiation, the second pulse of radiation having a greater intensity than the first pulse of radiation;

a vacuum chamber configured to receive a target material in an interior of the vacuum chamber, the target material comprising a material that emits EUV light when converted to plasma; and

an optical element configured to direct the first pulse of radiation and the second pulse of radiation toward the interior of the vacuum chamber to, respectively, a first location in the interior of the vacuum chamber and a second, different location in the interior of the vacuum chamber, the first and second locations in the interior of the vacuum chamber being along a direction that is different from a direction of propagation of the first pulse of radiation and the second pulse of radiation in the interior of the vacuum chamber.

2. The EUV light source of claim **1**, wherein the first pulse of radiation produced by the solid state laser has a first wavelength, and the second pulse of radiation produced by the second optical source has a second wavelength, the first and second wavelengths being different.

3. The EUV light source of claim **2**, wherein the first pulse of radiation has a wavelength of 1.06 microns (μm), and the second pulse of radiation has a wavelength of 10.6 μm.

4. The EUV light source of claim **1**, wherein the first pulse of radiation has a temporal duration of 5-20 picoseconds (ps).

5. The EUV light source of claim **1**, wherein the first pulse of radiation has a temporal duration of 150 ps or less.

6. An extreme ultraviolet (EUV) light source comprising:

a vacuum chamber configured to receive a target material in an interior of the vacuum chamber, the target material comprising a material that emits EUV light when converted to plasma;

a solid state laser configured to produce pulses of radiation, the pulses of radiation produced by the solid state laser comprising at least a first pulse of radiation, the first pulse of radiation propagating on a first beam path to a first location in the interior of the vacuum chamber; and

a second optical source configured to produce pulses of radiation, the pulses of radiation produced by the second optical source comprising at least a second pulse of radiation, the second pulse of radiation having a greater intensity than the first pulse of radiation, and the second pulse of radiation propagating on a second beam path to a second location in the interior of the vacuum chamber, the first and second locations in the interior of the vacuum chamber being different locations along a direction that is different from a direction of propagation of the first pulse of radiation and the second pulse of radiation in the interior of the vacuum chamber.

7. The EUV light source of claim **6**, further comprising an optical element placed on the first beam path and the second beam path, the optical element positioned to receive the first pulse of radiation and the second pulse of radiation and to direct the first pulse of radiation to the first location and the second pulse of radiation to the second location.

8. The EUV light source of claim **7**, wherein the optical element comprises a surface that is at least partially reflective.

9. The EUV light source of claim **7**, wherein the optical element transmits one of the first pulse of radiation and the second pulse of radiation, and reflects the other of the first pulse of radiation and the second pulse of radiation.

10. The EUV light source of claim **7**, wherein the wavelength of the first pulse of radiation is different from the wavelength of the second pulse, and the optical element comprises a dichroic mirror.

11. The EUV light source of claim **7**, wherein the wavelength of the first pulse of radiation is different from the wavelength of the second pulse, and the optical element comprises a wedge-shaped optical element that directs the first pulse and the second pulse toward the interior of the vacuum chamber at different angles relative to the optical element.

12. The EUV light source of claim **6**, further comprising a first optical element on the first beam path, wherein the first optical element directs the first pulse of radiation toward the first location in the interior of the vacuum chamber.

13. The EUV light source of claim **6**, further comprising a first optical element on the first beam path, and a second optical element on the second beam path, wherein the first optical element directs the first pulse of radiation toward the first location in the interior of the vacuum chamber, and the second optical element directs the second pulse of radiation toward the second location in the interior of the vacuum chamber.

14. The EUV light source of claim **13**, wherein the first optical element comprises one or more optical fibers.

15. The EUV light source of claim **6**, wherein the first pulse of radiation has a wavelength of 1.06 microns (μm), and the second pulse of radiation has a wavelength of 10.6 μm.

16. The EUV light source of claim **6**, wherein the first pulse of radiation has a temporal duration of 5-20 picoseconds (ps).

17. The EUV light source of claim **6**, wherein the first pulse of radiation has a temporal duration of 150 ps or less.

18. The EUV light source of claim **6**, wherein the target material comprises a target material droplet, and the EUV light source further comprises a target material delivery system coupled to the vacuum chamber, the target material delivery system configured to provide the target material droplet to the interior of the vacuum chamber.

19. The EUV light source of claim **18**, wherein the target material delivery system releases the target material droplet onto a trajectory in the interior of the vacuum chamber, and the first and second locations are on the trajectory.

20. The EUV light source of claim **19**, wherein the target material droplet comprises tin.

21. A photolithography system comprising:

a lithography tool configured to process wafers; and

an extreme ultraviolet (EUV) light source comprising:

a vacuum chamber configured to receive a target material in an interior of the vacuum chamber, the target material comprising a material that emits EUV light when converted to plasma;

an optical element in the interior of the vacuum chamber, the optical element positioned to direct EUV light to the lithography tool;

a first optical source configured to produce pulses of radiation, the pulses of radiation produced by the first optical source comprising at least a first pulse of radiation, the first pulse of radiation propagating on a first beam path to a first location in the interior of the vacuum chamber; and

a second optical source configured to produce pulses of radiation, the pulses of radiation produced by the second optical source comprising at least a second pulse of radiation, the second pulse of radiation having a greater intensity than the first pulse of radiation, and the second pulse of radiation propagating on a second beam path to a second location in the interior of the vacuum chamber, the first and second locations in the interior of the vacuum chamber being different locations along a direction that is different from a direction of propagation of the first pulse of radiation and the second pulse of radiation in the interior of the vacuum chamber.

22. The photolithography system of claim **21**, wherein the first optical source comprises a solid state laser.

23. A method comprising:

directing a first pulse of radiation toward a first location in a vacuum chamber of an extreme ultraviolet (EUV) source, the first location at least partially coinciding with a target material droplet comprising target material that emits EUV light when converted to plasma, and the first pulse of radiation comprising an intensity sufficient to transform the target material droplet into a geometric distribution of target material, the geometric distribution of target material occupying a larger volume than a volume occupied by the target material droplet; and

directing second pulse of radiation toward a second location in the vacuum chamber, wherein

the second location is a different location than the first location,

the second location at least partially coincides with the geometric distribution of target material,

the second pulse of radiation has a greater intensity than the first pulse of radiation.

24. The method of claim **23**, wherein the density of the geometric distribution increases along a direction of propagation of the second pulse of radiation.

25. The method of claim **23**, wherein the first pulse of radiation propagates along a first beam path, and the second pulse of radiation propagates along a second beam path.

26. The method of claim **23**, wherein the first pulse of radiation has a duration of 150 ps or less.

* * * * *